SCIENTIFIC RESULTS OF CRUISE VII OF THE CARNEGIE
DURING 1928-1929

OCEANOGRAPHY—I-A

OBSERVATIONS AND RESULTS IN PHYSICAL OCEANOGRAPHY

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Observations and Results in

Physical Oceanography

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Of the 110,000 nautical miles planned for the seventh cruise of the nonmagnetic ship Carnegie of the Carnegie Institution of Washington, nearly one-half had been completed on her arrival at Apia, November 28, 1929. The extensive program of observation in terrestrial magnetism, terrestrial electricity, chemical oceanography, physical oceanography, marine biology, and marine meteorology was being carried out in virtually every detail. Practical techniques and instrumental appliances for oceanographic work on a sailing vessel had been most successfully developed by Captain J. P. Ault, master and chief of the scientific personnel, and his colleagues. The high standards established under the energetic and resourceful leadership of Dr. Louis A. Bauer and his coworkers were maintained, and the achievements which had marked the previous work of the Carnegie extended.

But this cruise was tragically the last of the seven great adventures represented by the world cruises of the vessel. Early in the afternoon of November 29, 1929, while she was in the harbor at Apia completing the storage of 2000 gallons of gasoline, there was an explosion as a result of which Captain Ault and cabin boy Anthony Kolar lost their lives, five officers and seamen were injured, and the vessel with all her equipment was destroyed.

In 376 days at sea nearly 45,000 nautical miles had been covered (see map, p. iv). In addition to the extensive magnetic and atmospheric-electric observations, a great number of data and marine collections had been obtained in the field of chemistry, physics, and biology, including bottom samples and depth determinations. These observations were made at 162 stations, at an average distance apart of 300 nautical miles. The distribution of these stations is shown in the map, which delineates also the course followed by the vessel from Washington, May 1, 1928, to Apia, November 28, 1929. At each station, salinities and temperatures were obtained at depths of 0, 5, 25, 50, 75, 100, 200, 300, 400, 500, 700, 1000, 1500, etc., meters, down to the bottom or to a maximum of 6000 meters, and complete physical and chemical determinations were made. Biological samples to the number of 1014 were obtained both by net and by pump, usually at 0, 50, and 100 meters. Numerous physical and chemical data were obtained at the surface. Sonic depths were determined at 1500 points and bottom samples were obtained at 87 points. Since, in accordance with the established policy of the Department of Terrestrial Magnetism, all observational data and materials were forwarded regularly to Washington from each port of call, the records of only one observation were lost with the ship, namely, a depth determination on the short leg between Pago Pago and Apia.

The compilations of, and reports on, the scientific results obtained during this last cruise of the Carnegie are being published under the classifications Physical Oceanography, Chemical Oceanography, Meteorology, and Biology, in a series numbered, under each subject, I, II, and III, etc.

A general account of the expedition has been prepared and published by J. Harland Paul, ship's surgeon and observer, under the title The last cruise of the Carnegie, and contains a brief chapter on the previous cruises of the Carnegie, a description of the vessel and her equipment, and a full narrative of the cruise (Baltimore, Williams and Wilkins Company, 1932; xiii + 331 pages with 198 illustrations).

The preparations for, and the realization of, the program would have been impossible without the generous cooperation, expert advice, and contributions of special equipment and books received on all sides from interested organizations and investigators both in America and in Europe. Among these, the Carnegie Institution of Washington is indebted to the following: the United States Navy Department, including particularly its Hydrographic Office and Naval Research Laboratory; the Signal Corps and the Air Corps of the War Department; the National Museum, the Bureau of Fisheries, the Weather Bureau, the Coast Guard, and the Coast and Geodetic Survey; the Scripps Institution of Oceanography of the University of California; the Museum of Comparative Zoölogy of Harvard University; the School of Geography of Clark University; the American Radio Relay League; the Geophysical Institute, Bergen, Norway; the Marine Biological Association of the United Kingdom, Plymouth, England; the German Atlantic Expedition of the Meteor, Institut für Meereskunde, Berlin, Germany; the British Admiralty, London, England; the Carlsberg Laboratorium, Bureau International pour l'Exploration de la Mer, and Laboratoire Hydrographique, Copenhagen, Denmark; and many others. Dr. H. U. Sverdrup, now Director of the Scripps Institution of Oceanography of the University of California, at La Jolla, California, who was then a Research Associate of the Carnegie Institution of Washington at the Geophysical Institute at Bergen, Norway, was consulting oceanographer and physicist.

In summarizing an enterprise such as the magnetic, electric, and oceanographic surveys of the Carnegie and of her predecessor the Galilee, which covered a quarter of a century, and which required cooperative effort and unselfish interest on the part of many skilled scientists, it is impossible to allocate full and appropriate credit. Captain W. J. Peters laid the broad foundation of the work during the early cruises of both vessels, and Captain J. P. Ault, who had had the good fortune to serve under him, continued and developed that which Captain Peters had so well begun. The original plan of the work was envisioned by L. A. Bauer, the first Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington; the development of suitable methods and apparatus was the result of the painstaking efforts of his co-workers at Washington. Truly, as was stated by Captain Ault in an address during the commemorative exercises held on board the Carnegie in San Francisco, August 26, 1929, "The story of individual endeavor and enterprise, of invention and accomplishment, cannot be told."

Prior to the Carnegie observations on her last cruise, knowledge of the physical oceanography of the Pacific Ocean was unreliable, and in some parts entirely lacking. The Carnegie investigated many areas in which few, and sometimes no, observations had been made. Because of this, and because of the accuracy of the data gathered, the results presented in this volume are valuable.

Dr. H. U. Sverdrup, Director of the Scripps Institution of Oceanography, and F. M. Soule, of the Department of Terrestrial Magnetism, prepared the papers that comprise this volume. A considerable part of the work required in the reduction of the oceanographic observations was done by C. C. Ennis at the Department of Terrestrial Magnetism under the direction of Dr. J. A. Fleming, Director of the department. Mr. Ennis made a
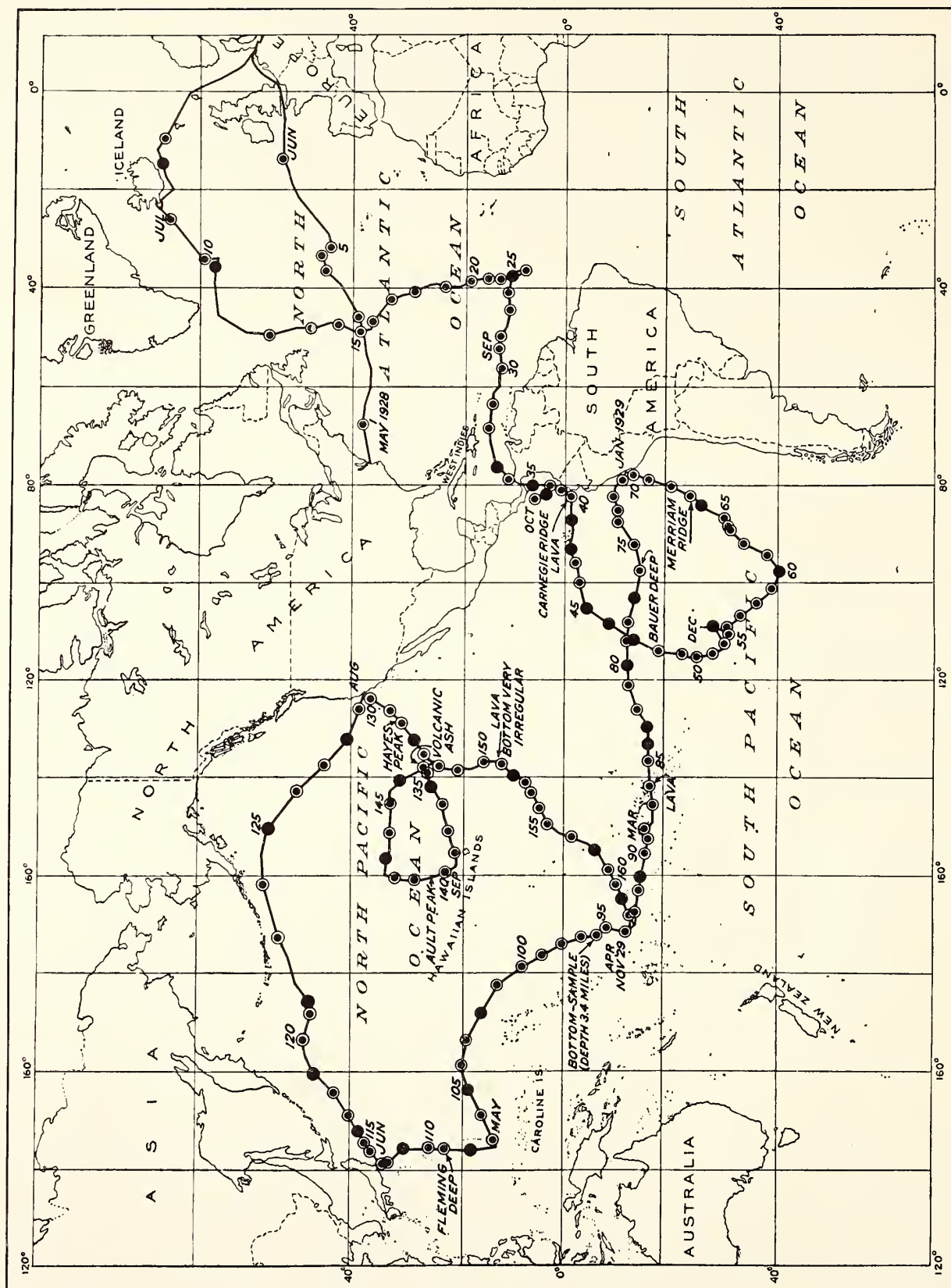
OCEANOGRAPHIC STATIONS, CRUISE VII OF THE CARNEGIE, 1928-29

(At the 35 stations marked ● true sea-water samples were also obtained for salinity calibrations)

great number of the computations and prepared all the figures.

Sonic depth finding equipment loaned by the United States Navy Department made a program of sounding possible. Although the program changed occasionally with changing conditions, soundings were usually made every four hours. These soundings reveal changes that have to be made in our conceptions of the most probable course of the depth contours in the oceanic areas traversed.

Salinities were measured by the bridge and titration methods, and then compared. The results of the salinity work are given in table 2 and in the vertical distribution curves (Oceanography I-B, pp. 183-257, and 56-115).

Bottom samples were collected at the different stations with various samplers. These samples were sent to Washington for examination.

In his introduction Dr. Sverdrup states that oceanographic data accumulated after 1930 have not been considered by him in preparing the present volume, and this procedure has imposed certain limitations on the discussion. On the other hand, the Carnegie data have been freely placed at the disposal of every oceanographer who has needed them in his work, and have, therefore, been widely used and discussed from different points of view. Dr. Sverdrup has himself used them most extensively, particularly in other analyses of the waters and currents of the Pacific Ocean such as those appearing in "The oceans, their physics, chemistry, and general biology" by himself, Johnson, and Fleming. These later analyses have not materially changed the conclusions.

The present volume is the seventh in the series "Scientific results of cruise VII of the Carnegie under command of Captain J. P. Ault." It is the first of the Oceanographic Reports.

J. A. Fleming
Director, Department of Terrestrial Magnetism

GENERAL CONTENTS

OBSERVATIONS AND RESULTS IN PHYSICAL OCEANOGRAPHY

I

OBSERVATIONS IN PHYSICAL OCEANOGRAPHY

CONTENTS

The water bottles used on the Carnegie for the routine collection of water samples were of the Nansen type manufactured by Bergen Nautik. This type of bottle consists of a hollow brass cylinder equipped with valves, one in each end. The valves are operated synchronously by means of a connecting rod which is attached to the clamp that secures the bottle to the cable. When the bottle is sent down, this clamp is at the lower end of the bottle, the upper end being held to the cable by a pin. When the bottle is in this position the valves are open. The cable is paid out until the bottle reaches the level from which a sample is desired. Then a concentric cylindrical brass weight called a messenger is placed on the cable and released from the surface. The messenger slides down the cable to the bottle where it trips a trigger, pulls the holding pin and thus releases the upper end of the bottle from the cable. The bottle falls over and in so doing closes the valves in either end; the valves are locked in the closed position by a spring, and the desired sample is trapped in the bottle. Figure 1 shows a Nansen water bottle. Normally a series of several bottles are placed on the cable at intervals along its length for a single cast. In such a case a messenger is placed on the cable just below each bottle (except the lowest) and temporarily held in place by a short chain, the last link of which is attached to the bottle by means of a spring pin. After the surface messenger releases the upper end of the first bottle, it slides on down the cable to the lower end of the bottle where it releases the attached messenger which, in turn, continues down the cable. The process is repeated at each bottle. The bottle is also equipped with an air valve, a stopcock, and a removable frame suitable for holding two deep-sea reversing thermometers. For further description of the Nansen type water bottle see Helland-Hansen and Nansen (1926).

The Nansen bottles used on the Carnegie were tinned and the exterior painted white. Because of the absorption of dissolved oxygen by tinned brass (see Knudsen, 1923) the tabulated oxygen values are possibly somewhat too low but are comparable with all but the most recent observations in which silver lined collecting bottles have been used.

Large water bottles such as the Allen and Meteor types, described respectively by Allen (1927) and Wüst (1926), were used infrequently at shallow depths for the collection of microplankton.

An instrument which it was thought would be of great usefulness is a small light reversing water bottle for use on the bottom sampling line to obtain water samples and temperatures from the layers immediately above the bottom. (See fig. 2). Such bottles originally were manufactured by Bergen Nautik for the Carnegie but arrived on board just prior to the disaster and so were not tried out. They operated on the propeller principle described below in connection with thermometer reversing frames. Their capacity was 300 ccm and their weight 2.32 kg without thermometers.

Thermometer reversing frames, such as the one shown in figure 3, were used at the end of the bottom sampling piano wire attached to the drift line about 20 meters from the end. Equipped with a protected and with an unprotected thermometer, the arrangement was used to determine the depth at which bottom samples were taken, and at the same time it gave measurements of the temperature close to the bottom. The frame containing the thermometers was hinged off center and held in position by a threaded pin which was withdrawn by the action of a small propeller when the line was being hauled in. Experiments near the surface indicated that upward motion through the water over a distance of about 25 meters served to reverse the thermometers.

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Knudsen, M. 1923. Some new oceanographical instruments. Conseil Perm. Internat. Expl. Mer., Pub. Circ. no. 77, pp. 10-12.

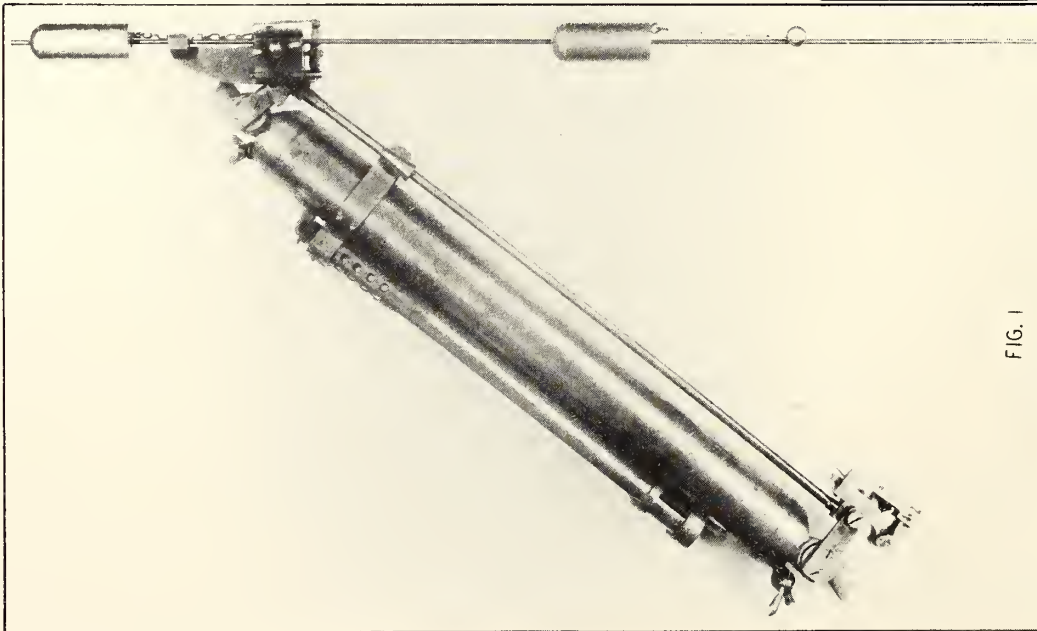Wüst, G. 1926. Bericht über die Ozeanographischen Untersuchungen. 2. Gesellsch. Erdk., Berlin, no. 1, p. 28.
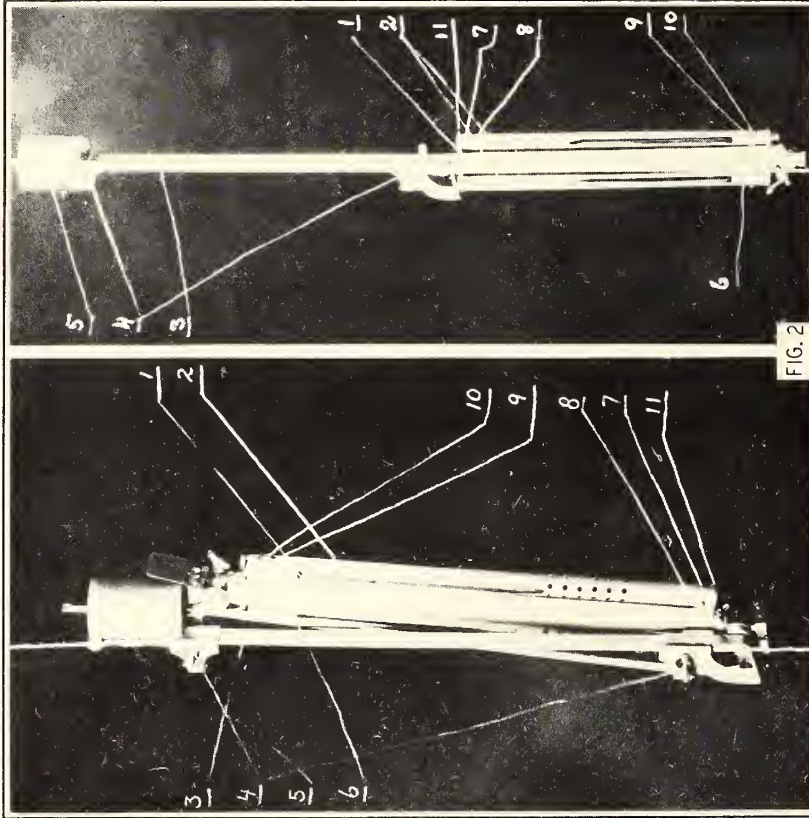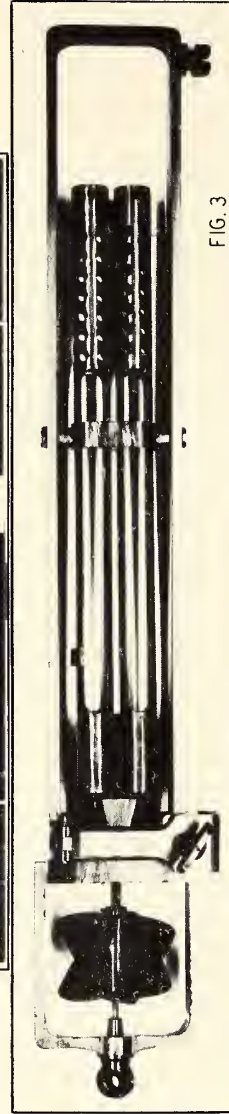
FIG. I—NANSEN WATER BOTTLE CLOSING

FIG. 2—PROPELLER OPERATED REVERSING WATER BOTTLE, OPEN AND CLOSED

FIG. 3—PROPELLER OPERATED THERMOMETER REVERSING FRAME

FIG. 2

FIG. 3

FIG. I

4

The surface temperature was recorded continuously by means of a sea-water thermograph. The instrument and its operation are described in the volume dealing with the meteorological data, and tables showing hourly values of sea-surface temperatures are given in that volume and in table 1 of Oceanography I-B. In the following, therefore, we are concerned with the subsurface temperatures only.

The subsurface temperatures were determined by means of protected reversing thermometers of the well-known pattern manufactured by Richter and Wiese.[1] All thermometers had been examined at the Physikalische Technische Reichsanstalt (PTR) and will be referred to by the PTR numbers. The corrections determined by the Reichsanstalt will be designated the "PTR corrections." Table 1 gives the range for each thermometer, the character of graduation, the date of the PTR certificate, and the numbers of the stations at which used.

From the footnotes in table 1 it is seen that a number of the thermometers were lost because of accidental breaking of cable during the occupation of several stations. The remaining thermometers were all lost when the Carnegie was destroyed. No determinations of the corrections of the thermometers were undertaken at sea and, since all thermometers were lost, a re-examination is impossible. A large number of protected thermometers were used in pairs, however, and from the differences between the corrected readings of two such thermometers it is possible to arrive at several conclusions as to the accuracy of the observed temperatures, assuming the PTR corrections to have remained unchanged.

Before entering on an examination of these differences, the possible errors of the temperature observations will be briefly discussed. Some of the thermometers were divided to one-twentieth degree and others to one-tenth. The errors of these two classes of thermometers, which for sake of brevity will be referred to as the one-twentieth and the one-tenth thermometers, will be treated separately. The following sources of error then have to be considered: (1) errors of reading; (2) correction errors arising from (a) reduction errors, (b) limit of accuracy of the test, and (c) change of zero point; and (3) errors of breaking-off device.

(1) Errors of reading. All thermometers were read to $0.^{\circ}01$ and reading was always made by means of a special reading lens. The accuracy of the reading, therefore, can safely be assumed to lie within the limits $\pm 0.^{\circ}01$. Böhnecke (1927) states regarding the one-twentieth thermometers that the errors of reading for such thermometers when read to $0.^{\circ}001$ never exceed $0.^{\circ}005$ and as a rule were smaller than $0.^{\circ}003$ according to the experience at the Reichsanstalt.

(2a) Correction errors arising from reduction errors. A correction, as is well known, must be applied to the reversing-thermometer reading, since as a rule it is read at a temperature differing from the temperature at which the column of mercury broke off. The exact formula for this correction is

$$(T + v_0)(T - t)/6100 \qquad (1)$$

[1] For detailed description see Wissensch. Ergebn. d. Deut. Atlantischen Exped. auf dem Forschungs- und Vermessungsschiff Meteor 1925-27, vol. 4, pt. 1. (1932).

where T is the temperature at which the thermometer was reversed, v_0 is the volume of the mercury at zero degree, t is the temperature at which the thermometer was read, and 6100 is a constant depending on the quality of the glass. The temperature at which the thermometer was reversed, however, is unknown and in the first approximation this temperature, T, may be replaced by the reading of the thermometer T'. As a second approximation, T' may be replaced by $(T' + dT')$, where dT' is equal to the correction which is computed by means of formula (1), using T' instead of T. The final formula for the second approximation to the correction will thus be

$$[(T' + v_0)(T' - t)/6100][1 + (T' + v_0) + (T' - t)/6100] \qquad (2)$$

This formula has been derived by Schumacher (1923) and represents an improvement of formula (1) commonly used. He shows that in extreme cases it may be necessary to apply still another approximation in order to reduce the reduction error beyond the values of the errors of reading, but in the case of the Carnegie observations the errors in the correction, K, as computed by means of formula (2) never exceeded $0.^{\circ}002$ and therefore may be disregarded. A practical method of determining the correction has been described by Soule (1933).

(2b) Correction errors arising from limit of accuracy of the test. The corrections of the thermometers which were communicated by the PTR and which must be applied in addition to the reduction correction, K, have been rounded to $0.^{\circ}01$. The corrections may be regarded as exact within $0.^{\circ}005$ at the time when the thermometers were tested; however, the corrections are likely to change with time and, according to the experience of the Meteor expedition, this change has the character of a parallel displacement of the correction curve supposing the breaking-off device always to function properly Wüst (1928). The parallel displacement of the correction curve may be attributed to a change of the zero point of the thermometer.

(2c) Correction errors arising from change of zero point. A change of the zero point of the thermometer takes place as a rule some time after the manufacture of the thermometer and in most cases may be ascribed to a contraction of the bulb which causes a rise of the zero point and thus a decrease in the correction which has to be applied at $0°$. The contraction of the bulb is hastened by artificial aging of the thermometers but the process usually continues for a long time afterward at a slower and slower rate. During the Meteor expedition Böhnecke examined the zero points of the greater number of the thermometers of the expedition at intervals of about two months. From this examination it appears that the zero point as a rule rose during the first two to six months after the manufacture and that no appreciable changes took place later. In several instances a lowering of the zero point occurred before the subsequent rise, this type of change being characteristic of instruments of very recent manufacture. In a few instances the variations were irregular evidently because of bad functioning of the break-off device. These thermometers were easily recognized when used together with a perfect thermometer because the differences in the indications would vary irregularly within considerable limits. Only in two cases were great variations of the zero point observed ($0.^{\circ}6$

Table 1. Thermometers used on the <u>Carnegie</u>, cruise VII

Fabr. no.	PTR no.	Date of PTR cert.	Grad-uation	Range	Used at stations
		1927	°	° °	
1604	127552	Oct 31	1/10	-1 - 30	1-162
1605[a]	127553	31	1/10	-1 - 30	1- 31
1606[a]	127554	31	1/10	-1 - 30	1- 31
1607[a]	127555	31	1/10	-1 - 30	1- 31
1608[a]	127556	31	1/10	-1 - 30	1- 31
1609	127557	31	1/10	-1 - 30	1-162
1610	127558	31	1/10	-1 - 30	1-162
1611	127559	31	1/10	-1 - 30	18-150
1621	127075	Nov 9	1/10	9 - 30	1-162
1622	127076	9	1/10	9 - 30	1-162
1623	127077	9	1/10	9 - 30	1-110
1624	127078	9	1/10	9 - 30	1-162
1625	127079	9	1/10	9 - 30	1-110
1626	127080	9	1/10	9 - 30	2-117
1627	127081	9	1/10	9 - 30	1-162
1628	127082	9	1/10	9 - 30	1-162
1629	127083	9	1/10	9 - 30	1-162
1630	127084	9	1/10	9 - 30	1-151
1631	127085	9	1/10	9 - 30	1-162
1632	127086	9	1/10	9 - 30	1-162
1633	127087	9	1/10	9 - 30	4-162
1634	127088	9	1/10	9 - 30	2-162
1635	127089	9	1/10	9 - 30	2-162
1641	127584	30	1/20	3 - 13	8-162
1642	127585	30	1/20	3 - 13	7-162
1643[b]	127586	30	1/20	3 - 13	7-151
1644	127587	30	1/20	3 - 13	7-156
1645	127588	30	1/20	3 - 13	7-152
1646[a]	127589	30	1/20	3 - 13	8- 30
1647[a]	127590	30	1/20	3 - 13	8- 30
1648	127591	30	1/20	3 - 13	....
1649[a]	127592	30	1/20	3 - 13	17- 31
1650[a]	127593	30	1/20	3 - 13	7- 31
		1928			
1658[b]	502	Jan 3	1/20	-2 - 8	33-150
1659	503	3	1/20	-2 - 8	33-162
1660[b]	504	3	1/20	-2 - 8	30-150
1661[a]	505	3	1/20	-2 - 8	1-131
1662[b]	506	3	1/20	-2 - 8	46-150
1663[a]	507	3	1/20	-2 - 8	1- 31
1664[a]	508	3	1/20	-2 - 8	1- 31
1665[c]	509	3	1/20	-2 - 8	11- 49
1666[a]	510	3	1/20	-2 - 8	1- 31
1667[a]	511	3	1/20	-2 - 8	3- 31
1668[a]	512	3	1/20	-2 - 8	11- 30
1669[a]	513	3	1/20	-2 - 8	11- 30
1670	514	3	1/20	-2 - 8	3-162
1671	515	3	1/20	-2 - 8	51-165
1672[a]	516	3	1/20	-2 - 8	1- 31
1930	3376	Oct 18	1/20	3 - 13	81-162
1931	3377	18	1/20	3 - 13	81-153
1932	3378	18	1/20	3 - 13	72-162
1933[d]	3379	18	1/20	3 - 13	81-154
1973	4246	Dec 6	1/10	9 - 30	113-162
1978	4251	6	1/10	9 - 30	113-162
1979	4252	6	1/10	9 - 30	113-162
1985[d]	4258	6	1/10	9 - 30	154-155
1879	4259	6	1/20	3 - 13	113-162
1912	4260	6	1/20	-2 - 8	....
		1929			
2094	158	Mar 6	1/20	-2 - 9	33-162
2095[b]	159	6	1/20	-2 - 9	115-150
2096[e]	160	6	1/20	-2 - 9	113-142
2097[b]	161	6	1/20	-2 - 9	116-150
2098[b]	162	6	1/20	-2 - 9	116-150
2099[b]	163	6	1/20	-2 - 8	116-150
2100	197	15	1/10	-2 - 30	116-162
2101	198	15	1/10	-2 - 30	116-162

Table 1. Thermometers used on the <u>Carnegie</u>, cruise VII--Continued

Fabr. no.	PTR no.	Date of PTR cert.	Grad-uation	Range	Used at stations
		1929	.°	° °	
2102	199	Mar 15	1/10	-2 - 30	118-162
2103[b]	200	15	1/10	-2 - 30	118-150
2104[b]	201	15	1/10	-2 - 30	118-150
2105	202	15	1/10	-2 - 30	118-162
2106[b]	203	15	1/10	-2 - 30	118-150
2108	205	15	1/10	-2 - 30	119-162
2109	206	15	1/10	-2 - 30	119-162
2060	264	Apr 12	1/20	-2 - 9	130-132
2243[b]	908	Aug 3	1/20	-2 - 9	131-150
2244[b]	909	3	1/10	-2 - 30	142-150
108	37339		1/10	-5 - 16	50-109
151	40661		1/10	9.5 - 30	32
48040	67955		1/10	-2 - 26	22- 28
48066	67958		1/10	-2 - 26	37- 87
1285	88700		1/10	10 - 35	17- 21
1336[a]	93687		1/10	-2 - 29	17- 31
1338	93699		1/10	-2 - 29	37- 39
1339	93690		1/10	-2 - 29	29-112

[a]Lost at station 32. [b]Lost at station 151. [c] Lost at station 49. [d]Lost at station 156. [e]Lost at station 144.

and 0.°8), perhaps owing to the opening of a bubble in the glass. Böhnecke states that the amplitude of the change of the zero point amounts on the average in the case of the one-twentieth thermometers to 0.°015 and in case of the one-tenth thermometers to 0.°02, the corresponding maximum values being 0.°035 and 0.°08. In this connection it may be mentioned that the corrections at zero scale division of the fifteen reversing thermometers used on the <u>Maud</u> expedition were determined at the Reichsanstalt in 1909, 1910, or 1914. The redeterminations made in 1922 to 1924 showed these corrections had remained unchanged in eight cases, had increased by 0.°01 in two cases, had decreased by 0.°01 in four cases, and by 0.°03 in one case, the mean change being -0.°003 and the maximum -0.°03. These results cannot be compared with the results of the <u>Meteor</u> expedition because the small changes of the Maud thermometers may be ascribed to the circumstance that the PTR calibration had taken place a considerable time after the completion of the thermometers by the manufacturer. In the case of the <u>Carnegie</u> thermometers, the possibility exists that the changes in the zero point may reach the amounts which Böhnecke found for the <u>Meteor</u> thermometers. Any considerable change of the zero point of one thermometer, however, can be detected if this thermometer had been used together with others and examinations of the differences between thermometers which were used in pairs should give valuable information. On the basis of experience on the <u>Meteor</u> it must be expected furthermore that thermometers received in 1929 would show slightly lower temperatures that those received in 1928, because it must be assumed that the zero point has risen more for the older thermometers. It must also be expected that the temperatures based on the original PTR corrections on the whole will be slightly too high because of the rise of the zero point but the mean error due to this circumstance will hardly exceed 0.°02.

(3) Errors of the breaking-off device. The errors arising from this source can be examined by repeating with the shortest possible interval of time the determination of the zero point of the thermometer or by comparisons between a perfect and an imperfect thermometer. The number of thermometers which do not function properly, according to Böhnecke's experience, is very small and the errors are seldom greater than ± 0°02. The possible errors are probably somewhat greater for the one-tenth thermometers and the limits are estimated to be ± 0°03. It happens, however, that the imperfect thermometers behave erratically and give readings which must be rejected because they are obviously wrong. Even a thermometer which as a rule functions reliably may for unknown reasons give erroneous results, but such cases ordinarily can be detected, especially if two thermometers have been attached to the same water bottle.

The preceding discussion can be summarized as follows:

Source of error	Thermometer graduated to 1/20°		Thermometer graduated to 1/10°	
	Probable error	Maximum error	Probable error	Maximum error
	°	°	°	°
(1) Reading	±0.003	±0.005	±0.005	±0.01
(2a) Reduction	0.000	±0.002	0.000	±0.002
(2b) Limited accuracy of test	±0.003	±0.005	±0.003	±0.005
(2c) Change of zero point	-0.015	+0.02 to -0.035	-0.02	+0.02 to -0.08
(3) Breaking-off device	0.000	±0.02	0.000	±0.03

The probable error of a single temperature determination by means of a one-twentieth thermometer not again examined after the PTR test, according to this compilation, lies between the limits -0°009 and -0°021, and the possible errors lie between the limits 0°052 and -0.067. The corresponding limits in the case of a thermometer which is graduated to 0°1 are -0°012 to -0°026 and 0°067 to -0°127, respectively. These limits are only approximate and especially the maximum errors must be regarded as roughly estimated and probably too great, but they furnish a basis for a discussion of the possible differences between the indications of two thermometers used simultaneously.

The differences between the indications of two thermometers which have been used together can be ascribed to the same sources as the errors of one single thermometer and we can, therefore, discuss these differences in the same sequence.

(1) Differences owing to errors of reading. Taking account of the maximum errors as stated in the preceding paragraph, these differences may reach ±0°01 and ±0°02 respectively, but are, as a rule, considerably smaller than ±0°01 and disappear when averaging many comparisons.

(2a) Differences arising from reduction errors. These differences are always negligible because the possible reduction errors, which are smaller than 0°002, have the same sign for both thermometers.

(2b) Differences owing to errors arising from limit of accuracy of the test. These differences are systematic for a given pair of thermometers but cannot exceed ± 0°01.

(2c) Differences owing to change of zero point. The differences owing to changes of the zero point may reach appreciable values because it is not probable that the zero points of two thermometers change in the same amount although the changes may have the same sign for both thermometers. The difference has a systematic character and is not eliminated when forming the mean value from many comparisons. If two thermometers are compared during a long period, it is to be expected that the difference will change in the course of time because it is not probable that the changes of the zero points of the two thermometers are at the same rate. Furthermore it must be expected that a new thermometer will give slightly lower temperatures than an old thermometer because the zero point of the older thermometer has risen more. The differences owing to change of zero point, according to the experiences of Dr. Böhnecke, may amount to 0°055 for the one-twentieth thermometers and to 0°10 for the one-tenth thermometers. The sign of the difference depends only on whether the indication of the thermometer giving the lowest reading is subtracted from the others or vice versa.

(3) Differences arising from errors of the breaking-off device. These differences may amount to ±0°04 or ±0°06 respectively but as a rule they are insignificant because most of the thermometers function perfectly. The differences are not systematic and therefore do not influence the mean value of the difference.

The results of this discussion are summarized below:

Source of difference	Thermometer divided to 1/20°		Thermometer divided to 1/10°	
	Probable	Maximum	Probable	Maximum
(1) Reading	±0.005	±0.01	±0.01	±0.02
(2a) Reduction	0.000	0.000	0.000	0.000
(2b) Limited accuracy of test	0.003	0.01	0.003	0.01
(2c) Change of zero point	0.015	0.055	0.020	0.10
(3) Breaking-off device	0.000	±0.04	0.000	±0.06

From this compilation it appears that for one comparison the probable difference between two thermometers which both are divided to 1/20° is 0°023 and on the average for a number of comparisons it is 0°013 because the errors of reading cancel. In order to find the range over which the differences may be distributed we have to take into account the maximum differences which may result from errors of reading and errors of the breaking-off device, considering that the errors due to limited accuracy of test and from change in zero point are systematic. Assuming these differences to be negative we find the limits -0°068 to +0°032, and assuming the difference to be positive we find the limits -0°032 to +0°068, and in both cases a range of 0°100. This range is reduced to 0°020 if the breaking-off device functions perfectly. The maximum value of the difference at one single comparison is 0°115 and the maximum average value of many comparisons is 0°066 with a range of 0°100 as before. In case of the thermometers which are

divided to 1/10° we find a probable difference of 0.°033 at one single comparison and a probable average difference of 0.°023, the maximum range of the differences being 0.°160 or 0.°040 if the breaking-off device functions perfectly. The corresponding maximum values are 0.°190 and 0.°110 with a range of 0.°160. From this discussion it appears that a study of the differences between the corrected readings of thermometers, which have been used in pairs, will help to clarify the question about the probable and possible errors of the single temperature observations.

Table 2 contains the results of the comparisons between thermometers which were divided to 1/20°. Here the reduced reading of the thermometer with the highest PTR number has been subtracted from the reduced

Table 2. Comparisons between thermometers which were divided to one-twentieth of a degree

PTR nos.	No. of comparisons	Mean difference	Range	Used at stations
		°	°	
127584-127585	4	-0.024	0.014	152-157
127585-127586	35	0.006	0.045	7- 60
127585-3378	38	0.005	0.031	72-114
127585-161	16	-0.004	0.026	116-134
127586-503	29	-0.025	0.016	78-114
127586-514	10	-0.017	0.041	61- 77
127586-3376	3	0.006	0.021	121-126
127586-909	5	-0.015	0.010	142-149
127587-127588	5	0.004	0.010	7- 13
127589-127590	7	-0.005	0.022	8- 30
127592-127593	10	-0.017	0.019	17- 31
127593-514	7	-0.004	0.030	7- 14
502-503	21	-0.003	0.017	32- 52
502-504	38	0.004	0.049	53- 91
505-508	19	-0.002	0.024	3- 31
507-510	20	0.012	0.039	3- 31
512-513	7	0.008	0.038	11- 30
3376-3379	4	0.006	0.030	81- 91
3376-3378	2	0.003	0.012	116-118
3378-3379	2	-0.014	0.009	152-153
158-159	15	-0.003	0.025	115-132
161-908	10	0.050	0.016	140-150

reading of the thermometer with the lowest PTR number. The signs of the differences are, therefore, accidental and on the average for all thermometers the difference ought to disappear. The table also gives the number of comparisons for the different pairs, the average difference, the range of the differences, and the number of stations at which the thermometers were used together. The last-named information is not complete inasmuch as only the first and last stations at which thermometers were used have been entered.

Table 3 contains the corresponding information for the cases in which one of the thermometers was divided to 1/20° and the other to 1/10°, and table 4 for the cases in which both thermometers were divided to 1/10°. It should be noted that a total of thirty-six cases has been omitted when preparing these tables because the differences were so great that one of the thermometers obviously was out of order.

From these tables it is seen that the mean difference reaches or exceeds the value of 0.°03 in three cases only. The difference (161-908) is 0.°05 and this difference must be attributed to an error in the correction of

thermometer 908 because 161 was used in combination with 127585 and 203, and was found in agreement with these. In order to bring thermometer 908 in agreement with the others we must change the correction of this thermometer by +0.°05. This has been done in the final revision of the temperatures. The other conspicuous

Table 3. Comparisons between thermometers which were divided to one-twentieth or one-tenth of a degree

PTR nos.	No. of comparisons	Mean difference	Range	Used at stations
		°	°	
127552-127584	50	0.020	0.053	92-151
127552-514	10	-0.005	0.032	152-162
127557-502	26	-0.012	0.036	92-119
127558-127584	1	0.015	....	158
127077-127587	6	0.005	0.013	36- 46
127585-37339	9	0.016	0.031	61- 71
502-200	15	0.013	0.056	133-150
503-198	11	0.015	0.031	152-162
3376-205	11	0.013	0.041	153-162
3378-203	6	0.005	0.021	121-126
3379-4258	1	0.015	....	154
3379-4259	6	0.004	0.026	121-126
159-201	17	0.001	0.035	133-150
161-203	3	0.003	0.017	136-139
37339-514	2	-0.042	0.031	59- 60

Table 4. Comparisons between thermometers which were divided to one-tenth of a degree

PTR nos.	No. of comparisons	Mean difference	Range	Used at stations
		°	°	
127552-127557	91	0.010	0.050	1- 91
127554-127556	29	-0.004	0.040	1- 31
127555-127558	3	0.007	0.060	1- 2
127558-127075	4	-0.002	0.010	3- 6
127558-198	37	0.009	0.070	116-151
127559-127076	20	-0.008	0.044	40- 60
127559-127087	7	-0.001	0.032	20- 36
127559-67958	3	0.023	0.028	37- 39
127075-127076	34	-0.027	0.065	127-162
127076-127077	31	0.011	0.066	1- 34
127076-127078	53	0.013	0.064	61-115
127077-127079	29	0.000	0.069	74-110
127077-37339	6	0.030	0.024	51- 58
127078-127079	24	-0.008	0.066	1- 32
127078-127089	11	-0.015	0.044	152-162
127080-127086	9	0.008	0.030	105-117
127081-127082	126	0.007	0.067	1-162
127083-127084	22	-0.014	0.060	1- 30
127084-127088	38	0.017	0.058	33- 70
127084-127088	48	-0.008	0.055	71-117
127085-127086	30	-0.024	0.063	1- 43
127085-127086	98	0.007	0.061	44-162
127087-127089	46	0.008	0.083	44-118
127087-127088	27	-0.001	0.034	136-162
127087-203	6	0.005	0.040	127-135
127088-127089	23	-0.001	0.031	2- 32
127089-206	4	0.006	0.019	148-151
4251-4252	16	-0.008	0.045	113-162
199-206	25	0.003	0.033	121-147
200-201	14	0.000	0.037	118-132
202-203	3	-0.028	0.051	118-120
202-205	29	0.003	0.066	121-151
202-4259	10	-0.004	0.048	152-162
205-206	2	0.012	0.005	119-120

differences are: (37339-514) = -0.°041 and (37339-127077) = -0.°30. The first of these differences, -0.°041, cannot be given any great weight because it is based on two comparisons only. In these combinations thermometer 37339 is an old thermometer which was examined at PTR in 1910 and re-examined in 1918 and 1922 to 1924. On these three occasions the same correction at zero was found. It should be expected, therefore, that 37339 gives correct temperatures. The results may be inter- preted to mean that the two new thermometers, 514 and 127077, gave temperatures too high. Thermometer 37339 was used in combination with a third new ther- mometer and the difference had the same sign also in this case, namely, (339-127585) = -0.°016. Considering that we should expect the zero point of the new thermom- eter to rise, it is indeed probable that these gave tem- peratures which were slightly too high when corrected by means of the original PTR values and that the cor- rections of the three thermometers 127077, 514, and 127585 actually should be lowered by about 0.°02 or 0.°03. Another old thermometer, 67958, was used in combina- tion with one of the new thermometers and the difference was of the same sign as above, being (67958-127559) = -0.°023. The correction of thermometer 127559 should thus, perhaps, be lowered by 0.°02. We have no possibil- ity of estimating the possible changes in all the other thermometers, however, and it therefore seems inad- visable to introduce any changes in these isolated cases, especially since the mean differences always are based on less than ten comparisons and therefore are uncer- tain. Instead of changing the original PTR correction we shall estimate, on the basis of the differences in tables 2, 3, and 4, the possible errors which are introduced by retaining the PTR corrections.

When discussing the probable differences between two one-twentieth thermometers, it was found that this difference, as a rule, is not greater than 0.°013. From table 2 it is seen that, omitting 908, the difference is smaller than 0.°013 in fifteen of twenty-one cases and that the greatest observed difference is 0.°025. The dif- ferences in the change of zero point, thus, have not ex- ceeded 0.°025. The absolute change for each thermome- ter is unknown, but on the average this change has prob- ably amounted to -0.°015. Considering that it is not probable that two thermometers have been combined which have both changed appreciably, we can safely state that the systematic error of the single thermometers, as a rule, is smaller than 0.°02 and never greater than 0.°03.

The ranges over which the differences are distribu- ted give an idea of the errors of reading and of the breaking-off device and thus an idea of the error of one single temperature determination. The maximum range was estimated to 0.°100 and in case the breaking-off de- vice always functioned perfectly we should expect the range to remain smaller than 0.°020. We find that the range is smaller than 0.°020 in eight of twenty-one cases, the maximum range being 0.°049. We therefore may conclude that the errors of reading and of the breaking- off device never exceeded 0.°03 and, since the range is smaller than 0.°031 in sixteen of twenty-two cases, that the errors as a rule were smaller than 0.°015. The er- ror of one single temperature determination by means of these theremometers, therefore, is smaller generally than 0.°035, ranging from -0.°005 to -0.°035, and the error is in no case greater than ±0.°06.

Turning next to the thermometers which are divided to 1/10° we find no greater scattering of the mean

differences than in case of the one-twentieth thermometers The probable mean difference between the one-tenth thermometers was estimated to 0.°023 and the maximum difference to 0.°160. We find a difference which is small- er than 0.023 in twenty-nine of thirty-four cases, and a maximum difference of 0.°030. Since the expected aver- age change of the zero point for these thermometers is -0.°02, we may safely state that the systematic error of one single thermometer, as a rule, is smaller than 0.°025 and never exceeds 0.°035. The ranges of the dif- ferences are, as a rule, greater for these thermometers than for the one-twentieth thermometers as should be expected because both the errors of reading and of the breaking-off device inevitably are greater. The maxi- mum range was estimated to 0.°160 and in case the breaking-off device functioned perfectly, to 0.°040. We find that the range is smaller than 0.°040 in twelve of thirty-three cases and never greater than 0.°083. The errors due to reading and breaking-off may, therefore, reach 0.°05 but, as a rule, are considerably smaller than 0.°02. Thus the total error of one single temperature determination is, as a rule, smaller than 0.°045 and nev- er greater than 0.°085.

These conclusions are supported by an examination of the cases in which a one-twentieth thermometer was used simultaneously with a one-tenth thermometer. The mean differences are of the same order as before and do not exceed 0.°020, omitting thermometer 37339. The ranges usually are greater than for the one-twentieth thermometers but smaller than for the one-tenth ther- mometers. If we subtract the corrected readings of the one-twentieth thermometers from the corrected read- ings of the one-tenth thermometers, we find a positive difference in three and a negative difference in ten cases, omitting thermometer 37339. The unweighted mean difference is -0.°0035. From this result it appears that the corrections of the one-tenth thermometers have not changed more than the corrections of the one-twentieth thermometers. Since the corrected readings of the lat- ter are slightly higher, the zero point of these thermom- eters seems to have risen more than the zero point of the one-tenth thermometers. It should thus be safe to assume that the zero point of the one-tenth thermome- ters has, as a rule, not risen more than 0.°025 and never more than 0.°035.

When discussing the possible differences, attention was drawn to the circumstance that the differences be- tween the two thermometers which were compared dur- ing a long period should be expected to change, because the changes of the zero points of the two thermometers could not be assumed to follow each other. From table 4 it is seen that the differences between thermometers 127084 and 127088 and thermometers 127085 and 127086 have changed considerably, but the changes are in all other cases small. A noteworthy change in the differ- ence, therefore, seldom occurs. It was also mentioned that older thermometers probably would give slightly higher temperatures than more recently made thermom- eters because the zero point of the former had risen more. The cases in which a new thermometer was used together with an older one are compiled in table 5. A "new thermometer" is defined as one tested at PTR less than eight months before its use and an "old ther- mometer" is defined as one tested at least twelve months earlier than a new one. The values given are differences obtained by subtracting the reading of the new thermometer from that of the old one. It is seen

Table 5. Comparisons between thermometers which were used during July, September, October, and November, 1929, and had been calibrated either during October, November, 1927, or January, 1928 (old thermometers) or during March or August, 1929 (new thermometers)

Old minus new thermometer PTR no.	No. of compar- isons	Mean differ- ence	Range
		°	°
127558-198	37	0.009	0.070
127087-203	6	0.005	0.040
127089-206	4	0.006	0.019
127585-161	16	-0.004	0.026
127586-909	5	-0.015	0.010
502-200	15	0.013	0.056
503-198	11	0.015	0.031
Weighted mean		0.009	

Table 6. Temperature observations below a level of 2700 meters in the Peruvian basin

Station no.	Depth in meters	Thermometer no.	Temperature centigrade
69	2781	127502	1.83
	2781	127504	1.83
	3188	127506	1.81
70	2907	127558	1.82
	3333	127502	1.83
	3333	127504	1.83
	3760	127506	1.84
71	2963	127506	1.81
72	2781	127558	1.82
	3189	127502	1.82
	3189	127504	1.82
	3603	127506	1.84
74	2897	127558	1.84
	3313	127502	1.83
	3313	127504	1.82
	3735	127506	1.81
76	3181	127502	1.84
	3181	127504	1.83
77	2721	127506	1.84
78	2803	127502	1.82
	2803	127504	1.82
	3138	127506	1.82

that the differences are positive in five of the seven cases, the mean weighted difference being 0.009. The old thermometers thus give slightly higher temperatures than the new ones, as should be expected. The conclusions which were drawn from the results of Dr. Böhnecke's examination of similar thermometers are thus confirmed.

The final conclusion of this discussion is that most of the thermometers give temperatures which are systematically too high, but that the errors are as a rule smaller than 0°.02 and in no case greater than 0°.035. A single temperature observation may be affected also by accidental errors, which, as a rule are considerably smaller than 0°.02 and in the case of the one-twentieth thermometers never greater than 0°.03 nor more than 0°.04 in the case of the one-tenth thermometers. These accidental errors could not have been avoided but the systematic errors could have been reduced had it been possible to re-examine the thermometers after their use. The systematic errors, however, are so small that in most cases they are of no significance.

This conclusion is verified by an examination of the temperatures at great depth at stations in the Peruvian basin. Stations 68 to 79 are all located in this basin in which the water at great depths appears to be very uniform, since it is not in direct communication with water in adjacent areas. The observations from this region show that this is true because the same temperature is found at all stations below a depth of 2700 meters. The agreement between the individual observations is good as evident from the compilation in table 6.

From the data in table 6 we find the following mean values:

Thermometer nos.	127558	127502	127504	127506
Mean temperature, °C	1.827	1.828	1.825	1.824

and none of the individual values deviate as much as 0°.02 from these mean values. There is, thus, an excellent agreement between the four thermometers in question and the error of the individual observations appears to be well within the limits which were stated above.

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The thermometric method for determining depths in the sea has recently been discussed by Dr. A. Schumacher (1923) and part of this discussion will be repeated here for the sake of completeness. An unprotected thermometer which is subjected to a certain pressure will show a fictitious temperature which can be regarded as consisting of the actual temperature of the surroundings plus the effect of the compressibility of the glass. On account of this pressure effect the reading of the thermometer will be higher than the reading corresponding to the temperature of the surroundings and the increase of the reading per unit increase of pressure can be determined in laboratory. The difference between the indications of two thermometers, one protected against pressure and one unprotected, which both are subjected to the same pressure in the same surroundings, can on the other hand be used for determining the pressure, assuming the pressure coefficient of the unprotected thermometer to be known. This method is used in oceanographic work. Two thermometers, one protected and one unprotected, are attached to the same water bottle and the pressure at which the thermometers were reversed can be computed from the corrected readings. Knowing the average density of the water from the surface and down to the level where the thermometers were reversed, the depth can be found. Since the pressure coefficient of the thermometers is given in degree centigrade per kg/cm^2 of increase in pressure and since the pressure of 10 meters of water of density 1 is equal to 1 kg/cm^2, we get:

$$D = \frac{10 \, \Delta t}{q \cdot \rho m} \qquad (1)$$

where D means the depth in meters, Δ the difference between the corrected readings of the two thermometers, q the pressure coefficient of the unprotected thermometer, and ρ_m the mean density from the surface to the level at which the thermometers were reversed.

The corrections which must be applied to the reading of the protected reversing thermometer have already been discussed. The correction to be applied to the reading of the unprotected thermometer because it was read off at a temperature which differs from the temperature at which it was reversed, is found by means of the same formula:

$$K = \frac{(T_u + v_0) (Tp - t)}{6100} \qquad (2)$$

where T_u means the "temperature" of the unprotected thermometer v_0 the volume of mercury at zero degrees expressed in degrees, Tp the temperature at which the thermometer was reversed, t the temperature at which it was read off and where 6100 is a constant which depends on the quality of the glass. The temperature at which the thermometer was reversed is known exactly from the indication of the protected thermometer, but the indication of the unprotected thermometer at reversal is not known. As a first approximation the reading of the unprotected thermometer, T_u' is introduced in equation (2) instead of T_u. This introduction leads in the case of the Carnegie observations to errors which never exceed $0°005$ and may be regarded as negligible. The correction on account of the thermometer being read at a temperature which differs from the temperature at which

reversal has, therefore, been computed by means of the formula:

$$K = \frac{(T_u' + v_0) (Tp - t)}{6100} \qquad (3)$$

To the correction K the scale correction at the temperature of reading has to be added. Practical methods of determining this correction and of determining the depth have been described by Ennis (1933) and Soule (1933).

After these remarks about the corrections of the unprotected thermometers, we can turn to a discussion of the accuracy of the depth as determined by means of pressure thermometers (equation 1). Following the procedure of Schumacher, we compute the inaccuracy in the depth which would result from inaccuracy in the quantities Δt, q, and m:

1) $dD = \frac{10}{q \, \rho m} d\Delta t$ error in D arising from an error $d\Delta t$ in Δt

2) $dD = \frac{10 \Delta t}{q^2 \, \rho m} dq$ error in D arising from an error dq in q

3) $dD = \frac{10 \Delta t}{q \, \rho m^2} d$ m error in D arising from an error $d \rho_m$ in ρ

1. The pressure coefficient for the Carnegie thermometer values was between 0.07 and 0.09. For the mean density we may introduce 1.035. The factor $\frac{10}{q \, \rho m}$ lies, therefore, between the limits 138 and 107 and an error in the temperature difference of 0.01 introduces, therefore, an error of 1.4 to 1.1 meter. The error of the difference depends on the accuracy of the two thermometers. We have already discussed the accuracy of the protected reversing thermometers and have arrived at the conclusion that the error of one single temperature determination is, as a rule, considerably smaller than ±0.04 and never greater than ±0.075. As to the errors of the unprotected thermometers, we assume, since these have a more narrow division of the scale, that the errors may be twice as great--that means generally smaller than ±0.08 and never greater than ±0.15. The error in the difference between the corrected readings of a protected and an unprotected thermometer will therefore as a rule be considerably smaller than ±0.12 and never greater than ±0.225. The error in depth arising from these errors will usually be considerably smaller than ±16 and never greater than ±31 meters.

2. The pressure factor q, was determined at the Physikalische-Technische Reichsanstalt, Charlottenberg, and entered on the certificate of the thermometer to the fourth decimal place. Assuming the last decimal place to be correct (which means the error in the factor q to be smaller than 0.005), we find, taking ρ_m as a constant and equal to 1.035:

Maximum error in D	Temperature difference			
	10	20	30	40
q = 0.07	1	2	3	4
q = 0.09	1	1	2	2

The errors in depth introduced by the uncertainty in q appear thus to be small but it has to be considered that the pressure coefficient is not quite independent of the temperature and that it also may change in course of time, and the possible errors, therefore, are two or three times as great as those which are stated above.

3. The mean density of the water from the surface and to the level where the thermometers were reversed is easily determined with an accuracy of 0.0005. Assuming the mean value of the density to be constant and equal to 1.035 we find:

Maximum error in D	Temperature difference			
	10	20	30	40
$q = 0.07$	1	1	2	3
$q = 0.09$	1	1	2	2

The errors which are introduced on account of uncertainty as to the density are thus always small.

Summing up the results of this discussion, considering that a temperature difference of 10° roughly corresponds to a depth of 1250 meters, we find that the errors in the depth as determined by means of unprotected and protected thermometers probably lie within a limit

Depth in meters	Maximum error probably within
1000	±20
2000	±21
3000	±24
4000	±28
5000	±32

The errors of the thermometers enter here with the greatest weight.

In his discussion of the "Meteor" data, Wüst (1932) has shown that errors due to errors of coefficient q increase more with increasing depth than supposed here, but simultaneously he assumes the errors due to errors of reading to be smaller. His estimate of the greatest possible total error gives, therefore, smaller values at small depths, but greater values at great depths. He obtains, for instance, the values ±14 meters and ±49 meters at 1000 and 5000 meters, respectively, whereas our estimates are ±20 meters and ±32 meters. His final conclusion is that at depth below 1000 meters the mean accuracy of the thermometric determination of depth is from 0.6 to 0.4 per cent, whereas our final results, after discussion of the actual values, gives mean accuracy of about 1 per cent at 1000 meters and 0.5 per cent below 3000 meters.

In order to test this result, the cases have been examined in which the wire angle was equal to 5° or smaller. In these cases the wire length gives an accurate value of the depth and a comparison with the depths obtained by means of pressure thermometers furnishes data for an estimate of the possible errors in the thermometric determination of the depth. The cases in which the wire angle was from 6° to 10° were also studied as the depth corresponds closely to the wire length even when the angle is 10°. If the wire angle remained equal to 10° from the surface and down to the greatest depth, a wire length of 1000 meters would correspond to a depth of 985 meters, but as a rule the wire is curved and the difference between the wire length and the depth is smaller.

Table 1 contains the results of the comparisons between the depths as obtained by thermometers and the

Table 1. Differences between wire lengths and thermometer depths

PTR no.	Wire angle 0° to 5°				Wire angle 6° to 10°			
	No. of observations	Mean depth, meters	Mean difference, meters	Total range, meters	No. of observations	Mean depth, meters	Mean difference, meters	Total range, meters
838	6	365	- 0.5	14	6[a]	372	- 1.7	13
865	4[b]	145	- 3.0	10	3[a]	158	- 6.3	13
866	0[b]	......	....	...	4	608	6.0	21
868	2	2215	4.5	7	2	2898	23.5	5
869	2	1241	- 3.0	4	2	1237	8.5	19
990	...	......	....	...	1[b]	51	3.0	...
1688	...	......	....	...	1	51	6.0	...
1689	7	160	- 2.3	5	7	87	- 3.0	5
1690	16	409	- 2.4	21	12[b]	282	- 1.6	9
1691	11	193	- 2.7	10	6	274	- 0.5	6
1692	2	530	- 2.0	6	3[b]	174	0.3	13
1693	15	818	- 5.3	17	15	516	- 2.5	24
1694	...	......	....	...	1[b]	203	- 1.0	...
1695	18	257	- 2.1	13	16[a]	259	- 0.6	11
1696	8	2561	-20.9	37	14	2810	-13.1	45
1698	1	3072	-13.0	...	1	939	2.0	...
1699	1	4075	1.0	...	3	1283	10.3	31
1701	2	1645	9.0	22	2	199	- 7.0	4
1702	1	1021	0.0	...	1	547	8.0	...
1703	1	2042	0.0	...	2	1070	10.5	25
2993	2	3211	-23.0	18	2	3924	- 0.5	1
2994	2	1049	2.0	12	12	1123	10.0	19
2995	3	1104	0.0	16	9[b]	648	- 0.6	18
2996	5	1565	11.6	17	12	2005	14.9	35

[a]Two cases omitted.   [b]One case omitted.

Table 2. Number of cases where the difference lies between stated limits

Wire angle	Interval of difference: wire length minus thermometer depth in meters				
	0 to 5.0	5.1 to 10.0	10.1 to 15.0	15.1 to 20	20.1 to 25.0
0 to 5	14	2	2	0	2
6 to 10	12	7	4	0	1

wire length for the different pressure thermometers. The table gives the number of the thermometer, the number of observations with this thermometer, the mean difference between the wire length and thermometer depth, the total range of these differences, and the mean depth as obtained by thermometers. These data are entered for wire angles 0° to 5° and 6° to 10°.

An inspection of the table shows that the differences in depth between the wire lengths and thermometer depths as a rule are smaller than 5 meters if the wire angle is from 0° to 5° and smaller than 10 meters if the wire angle is from 6° to 10° (see table 2).

Only in three instances the mean difference is so great that an error in either the correction of the thermometers or the pressure factor seems to have influenced the mean difference. This applies to thermometers 1696, 2993, and 2996. According to an inspection of the single values it seems probable that the corrections of these thermometers have changed since they were determined at PTR and, since an error in the temperature correction introduces an error which is independent of depth, the simplest procedure is to apply a constant correction to the depths which are computed on the basis of the original temperature corrections. For the depths derived by means of these thermometers the following corrections have, therefore, been adopted:

Depth by thermometer 1696: correction: -20 meters;
Depth by thermometer 2993: correction: -10 meters;
Depth by thermometer 2996: correction: +10 meters.

After application of these corrections we find the following mean differences:

Wire angle 0° to 5°. Wire length minus thermometer depth: -1.9 meters (109 cases).
Wire angle 6° to 10°. Wire length minus thermometer depth: +3.2 meters (137 cases).

It is seen that the mean thermometer depth is slightly greater than the mean wire length in case the wire angle is between 0° and 5°. This result may be owing to systematic errors in the corrections of the thermometer (a greater rise of the zero point of the unprotected thermometers than of the protected thermometers would introduce an error of this sign) or it may be owing to a small systematic error of the meter wheel, used for measuring the wire length. It is of greater interest to state that the difference increases when the wire angle increases as should be expected.

Examining the total ranges of the differences we find that these are much smaller than the possible ranges which were estimated on the basis of the sources of errors. We found that these errors might lead to errors in the depth between +20 and -20 meters for depths smaller than 1000 meters, which means that the range of the differences between the exact values and the measured values of the depth might amount to 40 meters. At greater depths this range would be greater. When comparing the thermometer depth with wire length we have furthermore to bear in mind that the reading of the meter wheel may not indicate the exact wire length because the wire may have slipped on the wheel and we must, therefore, expect the ranges in table 1 to be greater than the estimated ranges (p. 12) provided that the errors of the thermometers are as great as supposed. From table 1, however, we find:

Table 3. Number of cases in which the total range of the difference, wire length minus thermometer depth, lies between stated limits

Wire angle	Limits of range in meters		
	0 to 20	21 to 40	41 to 60
0 to 5	13	3	0
6 to 10	13	5	1

From this compilation it is seen that the ranges are smaller than estimated, and this result leads to the conclusion that the accuracy of the temperature determinations is greater than supposed.

Grouping the differences and ranges according to the depths to which the thermometers have been used, we find the values which are entered in table 4.

Table 4. Differences between wire length and thermometer depth, and total ranges of these differences

Mean depth	Number of thermometers	Number of observations	Mean difference in meters	Maximum range
	Wire angle 0° to 5°			
0 to 1000	8	79	- 2.4	21
1000 to 2000	6	15	1.6	22
> 2000	6	15	- 2.4	37
	Wire angle 6° to 10°			
0 to 1000	16	88	- 1.1	24
1000 to 2000	4	19	9.9	31
> 2000	4	30	11.4	45

From this table it is seen that the difference is independent of depth if the wire angle is from 0° to 5° but the range of the differences increases with depth as was expected. If the wire angle is from 6° to 10° the difference increases with increasing wire length in agreement with the fact that the thermometer depth, if exactly determined, must be smaller than the wire length and the difference must increase with depth. In this case we find also that the maximum range increases with depth but the maximum ranges are greater than in case of the wire angle from 0° to 5°. The last result is easily accounted for by the fact that the curvature of the wire enters as an uncertain element if the wire angle is appreciable.

On the basis of the preceding discussion the accuracy of the thermometric determination of depth on board the <u>Carnegie</u> can be stated, assuming that the thermometers have functioned properly. Extrapolating to 6000 meters we find:

Depth	1000	2000	3000	4000	5000	6000
Accuracy of thermometric determination of depth in meters	±10	±12	±15	±20	±25	±30

This accuracy is highly satisfactory. It is evident that every uncertainty as to the depth, arising because of great wire angle, can be eliminated by attaching pressure thermometers to some of the water bottles along the wire.

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DETERMINATION OF DEPTHS AT WHICH TEMPERATURES WERE MEASURED

AND WATER SAMPLES COLLECTED

The length of the wire from the surface to the water bottle gives the exact depth only if conditions are so favorable that the wire remains vertical but if the drift of the vessel is great on account of surface currents or wind, or if considerable subsurface currents occur, the wire cannot be kept in a vertical position. An approximate value of the depth of a water bottle can then be computed from the length of the wire to the bottle and the wire angle at the surface, assuming the latter to remain constant. Such computation will generally render erroneous values for the depth, however, because the wire will, as a rule, not remain straight but will form a curve and the wire angle is, therefore, not constant but varies with depth. In most cases the wire angle decreases with depth and the assumption of a constant wire angle gives, therefore, too small values of the depth.

The Carnegie could not be maneuvered so readily that the wire could be kept approximately vertical under all conditions and great wire angles necessarily occurred. The knowledge of the depth at which temperatures were measured and from which water samples were brought up would, therefore, in many instances have been inaccurate if this should have been derived from wire lengths and wire angles only. On board the Carnegie, however, every second water bottle of the deep series was provided with one unprotected and one protected thermometer, and by means of the indications of these thermometers the depths of these water bottles could be found with an accuracy, which, according to the results in a preceding section (p. 11) was about ±10 meters at a depth of 1000 meters and ±30 meters at a depth of 6000 meters. Knowing the depth of several points of the wire with this accuracy, the curvature of the wire could be determined and the depth of the intermediate water bottles could be found. When taking the shallow series, down to 300 to 400 meters, two or more of the water bottles were also provided with unprotected thermometers and the indications of these were used for detecting any conspicuous deviation of the wire from a straight line. It was found, however, that at small depths no great errors were introduced by assuming the wire angle to remain constant.

The practical method, which was adopted for computing the depths on the basis of all available information, is best explained by means of an example. Table 1 contains the data from Carnegie station 71 (latitude 11° 57' south, longitude 78° 37' west). At this station, which was occupied on February 6, 1929, two series of water bottles were sent down. The wire angles observed on board are entered in the first column of the table and were 35° for the shallow and 40° for the deep series. The cosines of these angles are entered in the second column of the table. The third column contains the wire lengths to the different water bottles. Four of the seven water bottles of the deep series and two of the water bottles of the shallow series were provided with both protected and unprotected thermometers. From the indications of these thermometers, the depths have been computed which are entered in the fourth column of the table. The next column contains the factors by means of which the corresponding wire lengths must be multiplied in order to give these depths. These factors and the cosines of the wire angles have been plotted against wire lengths (fig. 1) and curves have been drawn representing the factors by means of which any wire length has to be multiplied in order to find the depth of that particular point on the wire. From the curves the factors have been read off for the intermediate wire lengths and entered in the fifth column of the table. The final depths in column six have been derived by multiplying the wire lengths (column three) with these factors.

From table 1 it is seen that the ratio between the

Table 1. Computation of depths at Carnegie station 71 (latitude 11° 57' south, longitude 78° 37' west, February 6, 1929) on the basis of thermometer depths and assuming the wire angle to be constant

1	2	3	4	5	6	7	8	9	10
Wire angle, °	Cosine of wire angle	Wire length, meters	Thermometer depths, meters	Ratio	Adopted ratio	Adopted depth, meters	Depth wire angle constant, meters	Observed temperature, °C	Observed salinities, °/oo
35	0.819	0	......	....	....	0	0	23.46	35.24
		5	......	....	0.810	4	4	23.30	35.26
		24	......	....	0.812	19	20	23.30	35.24
		49	......	....	0.814	40	40	18.15	35.14
		73	......	....	0.818	60	60	15.85	35.09
		98	......	....	0.820	80	80	14.30	35.02
		200	157	0.785	0.832	166	164	12.91	34.94
		295	......	....	0.842	248	242	11.76	34.87
		391	333	0.852	0.850	332	320	10.74	34.79
40	0.766	369	296	0.802	0.800	295	283	11.42	34.85
		628	......	....	0.811	509	481	8.16	34.64
		1016	838	0.825	0.825	838	778	5.29	34.54
		1652	......	....	0.847	1399	1265	3.15	34.62
		2250	1941	0.863	0.863	1941	1724	2.23	34.64
		2797	......	....	0.875	2447	2142	1.87	34.67
		3345	2963	0.886	0.886	2963	2562	1.81	34.68

wire length and the depth increases from the surface and down, meaning that the wire angle decreases. By means of the wire lengths and the actual depths of the different points on the wire, the curve which the wire formed at the time when the water bottles were reversed has been constructed and represented graphically in figure 2.

The straight line which is entered in figure 2 shows the position which the wire would have had if the wire angle had remained constant. It is seen that the actual depth of any given point on the wire is considerably greater than the depth corresponding to a constant wire angle. This fact is also evident from column 8 in table 1. This gives the depths which are derived by means of thermometer depths and wire length and the depths which are computed on the basis of a constant wire angle. In the table the observed temperatures and salinities have been entered. According to the values in the table, the temperatures and salinities were observed at greater depths than those which are obtained when assuming the wire angle to be constant. The discrepancy increases with depth and reaches an amount of 400 meters at a depth of about 2900 meters. Representing graphically the vertical distribution of the temperature, the temperature curve is displaced upward if the depths are derived from wire lengths and wire angle only. This example can be used for illustrating the importance of accuracy as to depth even when the vertical variation of the temperature in vertical direction is small. Station 71 is situated within an area where the temperatures are very uniform below 1800 meters. In figure 3 the temperatures at stations 68 to 79 have been plotted against depth. For station 71 double values have been entered, corresponding to the adopted depths, and corresponding to the depths which have been derived, assuming the

wire angle to be constant. It is seen that the former lie very nearly on the curve which is derived from the observations at the other stations in this region whereas the latter lie off this curve.

From the table it is seen that the depths of observations are always less than the wire length and that the difference increases with increasing wire length, reaching a value of 382 meters at a wire length of 3345 meters. These figures also demonstrate the importance of the direct determination of the depths at which the temperatures were measured and from which water samples were taken.

A compilation of the differences between wire lengths and actual depths of observation has not been undertaken and in the tables of results (Oceanography I-B) only the actual depths have been entered. At the greater number of stations these have been determined accurately by means of the above method, but in some instances the pressure thermometers have not functioned properly and the depths are, therefore, doubtful. In the tables of results special remarks are entered in each such case. In this place attention shall also be called to the fact that overlapping values of temperature and salinity have been obtained at a number of stations at which the greatest depth of the shallow series has been selected slightly greater than the smallest depth on the deep series. These overlapping values do not always fall on a smooth curve. The reason may be that a time change has taken place, but the reason may also be that the depths are slightly in error. An inspection of the temperature graphs shows that errors of ± 10 meters in the depth which as a rule would account for the discrepancies and errors of this magnitude are not excluded.
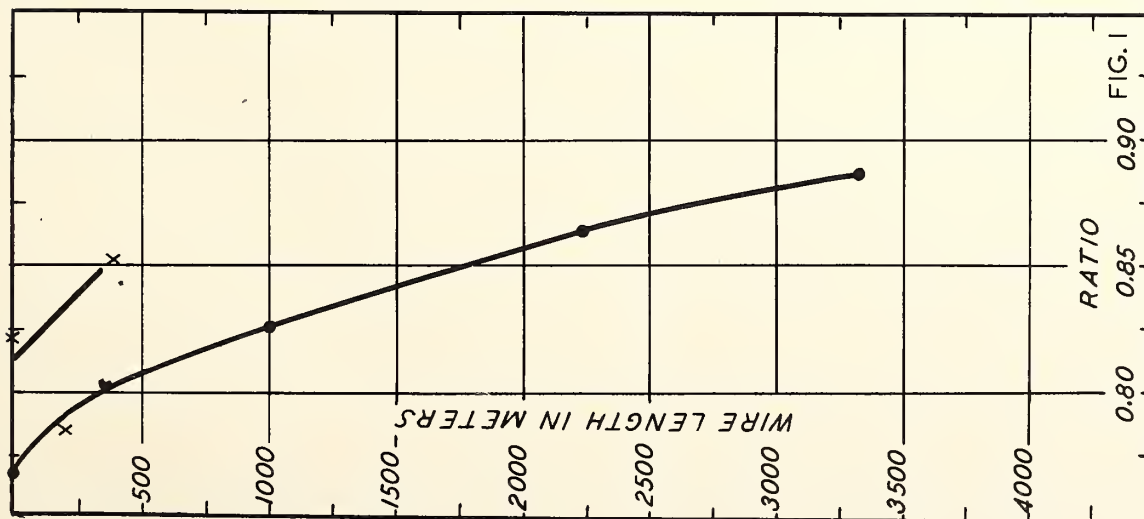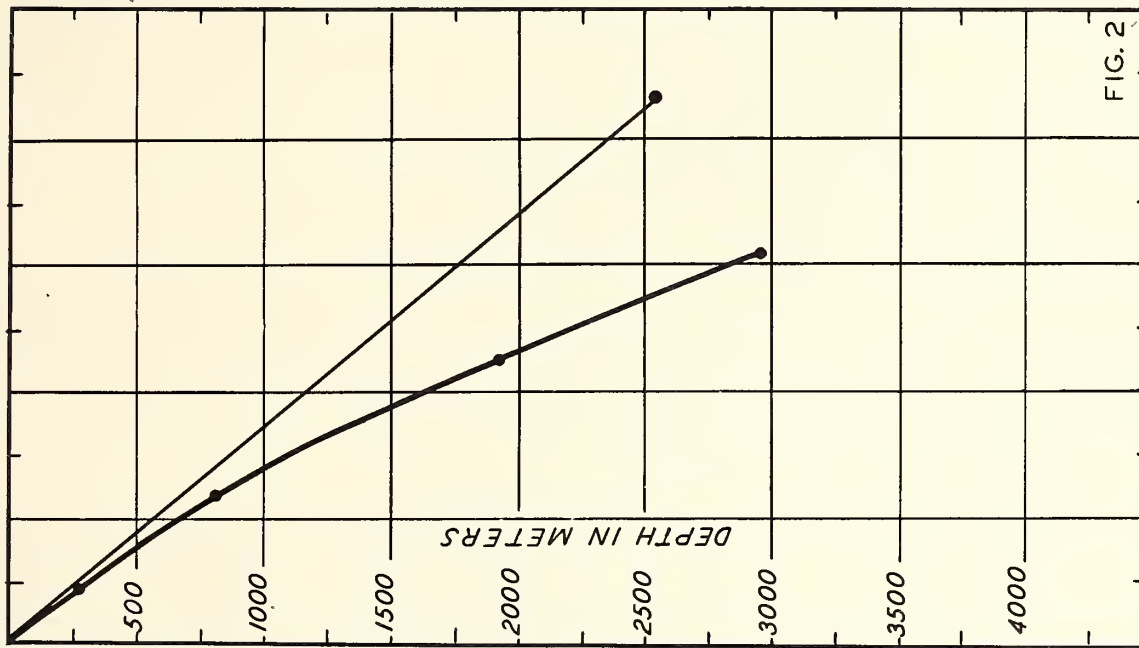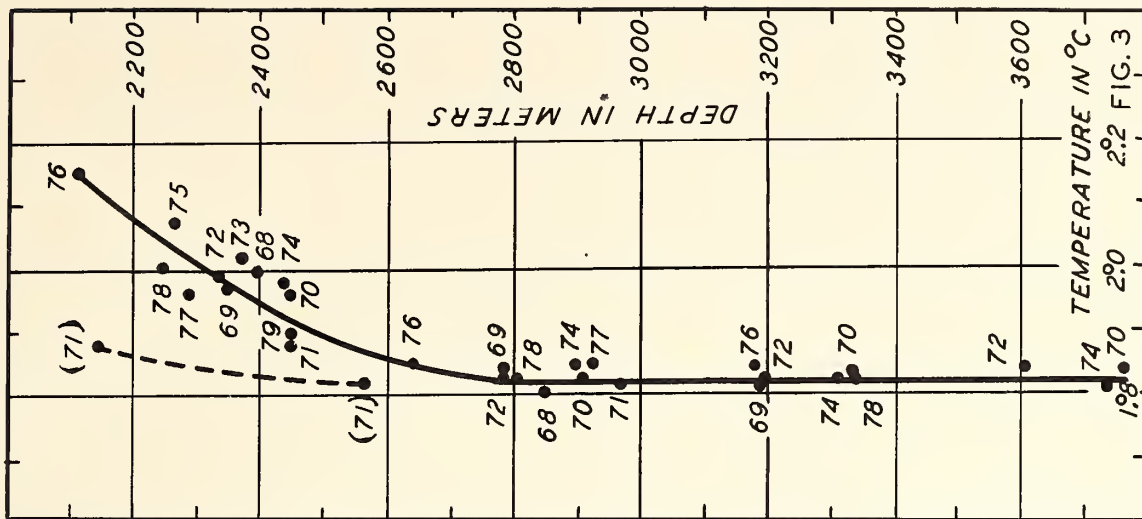
FIG. 1—RATIO BETWEEN DEPTH AND WIRE LENGTH AT CARNEGIE STATION 71 (X=RESULTS FROM SHALLOW SERIES; ●=RESULTS FROM DEEP SERIES)

FIG. 2—HEAVY LINE SHOWS CURVE FORMED WHEN WATER BOTTLES OF DEEP SERIES WERE REVERSED AND LIGHT LINE POSITION WIRE WOULD HAVE ASSUMED ON BASIS CONSTANT WIRE ANGLE AT CARNEGIE STATION 71

FIG. 3—TEMPERATURES AT DEPTHS BELOW 2000 METERS FOR CARNEGIE STATIONS 68 TO 79; VALUES FOR STATIONS ALSO SHOWN ON BASIS OF CONSTANT WIRE ANGLE

NOTE ON THE PRACTICAL CORRECTION OF DEEP-SEA REVERSING THERMOMETERS AND THE DETERMINATION OF THE DEPTH OF REVERSAL FROM PROTECTED AND UNPROTECTED THERMOMETERS

Because of its simplicity and its elementary character, little has been published regarding the actual steps involved in the practical reduction of the readings of the deep-sea reversing thermometers, protected and unprotected, to obtain temperatures and depths. Yet, judging from the number of requests for such information, there seems to be a need for its publication. The aim of this article is to supply that need and no claim of originality is made for the following.

In a reversing thermometer there are two corrections which must be applied. One is the index or scale correction, I, which arises from irregularities in the cross section of the capillary tube, and the other is a temperature-difference correction arising from the fact that the temperature at which the thermometer is read is usually different from the temperature at which it was reversed. The index correction is determined by calibration and is dependent only on the reading of the thermometer. As the temperature-difference correction is a correction for expansion, however, it depends on both the reading of the thermometer and the temperature at which it is read. Since the exact temperature-difference correction involves the temperature of reversal which is unknown, the practical formula used is an approximation which may take various forms. In the Russian Oceanographical Tables, 1931, compiled by N. N. Subow, S. W. Boujewicz, and Was. W. Shoulejkin, the correction for protected thermometers has the form

$$\Delta T = \left[\frac{(T' - t)\,(T' + v_O)}{K}\right]\left[1 + \frac{(T' + v_O)}{K}\right] + I$$

where ΔT is the total correction, T' is the reading of the main thermometer, t is the reading of the auxiliary thermometer (the temperature at which the reversing thermometer is read), v_O is the volume of mercury in the thermometer after reversal at $0°$ C expressed as degrees, K is a constant depending on the relative thermal coefficient of expansion of mercury and the glass of which the thermometer is made, and I is the index correction.

In the Memoirs of the Imperial Marine Observatory (1932), Koji Hidaka gives the correction for protected thermometers as

$$\Delta T = \frac{(T' - t)\,(T' + v_O)}{K\left[1 - \frac{(T' + v_O - t)}{K}\right]} + I$$

where the symbols all have the significance described above.

The correction given by Schumacher (1923) is, using the same symbols

$$\Delta T = \left[\frac{(T' - t)\,(T' + v_O)}{K}\right]\left[1 + \frac{(T' - t) + (T' + v_O)}{K}\right] + I$$

As an unprotected thermometer is used in conjunction with a protected thermometer, the temperature of reversal is known from the protected thermometer. The temperature-difference correction, in the case of an unprotected thermometer, is therefore more simple, and the total correction is

$$\Delta T = \frac{(T_W - t)\,(T' + v_O)}{K} + I$$

where T_W is the temperature of reversal as determined by the protected thermometer and where the other symbols have the same significance as before.

The constant K is determined by the quality of the glass, and is 6100 for Jena 59[iii] and 6300 for Jena 16[iii]. As most deep-sea reversing thermometers are made from either one or the other of these kinds of glass, it is possible to prepare a table, based on one or the other of these values of K, giving the value of the temperature-difference correction for different values of $(T' - t)$ and $(T' + v_O)$. If two tables are prepared, one for $K = 6100$ and one for $K = 6300$, it is then possible by their use to correct any protected thermometer whose index correction has been determined. Similar tables may also be prepared for unprotected thermometers, but such tables should give the correction for different values of $(T_W - t)$ and $(T' + v_O)$. Such tables may be converted into graphical form.

The time required at sea for reducing observations, however, is greatly lessened by the preparation ashore of complete correction graphs for individual thermometers. Such graphs may be constructed as follows: If C represents the temperature-difference correction, we have from Schumacher's formula for protected thermometers given above

$$C = \frac{(T' - t)\,(T' + v_O)}{K} + \frac{(T' - t)\,(T' + v_O)^2 + (T' - t)^2(T' + v_O)}{K^2}$$

or, rearranging

$$(T' - t)^2 \frac{(T' + v_O)}{K^2} + (T' - t)\left[\frac{(T' + v_O)^2 + K(T' + v_O)}{K^2}\right] - C = O$$

whence

$$(T' - t) = -\frac{(T' + v_O + K)}{2} + \sqrt{\frac{(T' + v_O + K)^2}{4} + \frac{K^2}{(T' + v_O)}C}$$

Now if the radical of the right-hand member of the above equation is expanded by the binomial theorem, we have

$$(T' - t) = \frac{K^2}{(T' + v_O + K)\,(T' + v_O)}C -$$

$$\frac{K^4}{(T' + v_O + K)^3(T' + v_O)^2}C^2 + \frac{2K^6}{(T' + v_O + K)^5(T' + v_O)^3}C^3 \cdots$$

Now T' is assigned a selected value near one extreme of the range of the thermometer and $(T' - t)$ is evaluated as C is assigned different values in steps of 0.01 from 0.00 to such a figure as will give the temperature

difference (T' - t) as large a value as is necessary to cover the anticipated conditions. Except in restricted environments (such as polar summers) this value of (T' - t) will probably be about 30° since water temperatures as low as about 0° may be expected, and reading temperatures as high as 30° are common. The process is then repeated with T' assigned an even-degree value near the other extreme of the range of the thermometer. For most thermometers, the first two terms on the right-hand side of the above equation determine the value of (T' - t) with sufficient accuracy.

The correction graph may now be constructed on cross-section paper with the readings of the reversing thermometer (T') as ordinates and the corrected readings of the auxiliary thermometer (t) as abscissae. A convenient scale is 0°1 to the millimeter. The length of the plotting sheet should be somewhat longer than three times the length of the finished graph which will occupy approximately the middle third of the original plotting sheet. On this graph the line of zero correction will be a 45°-line through all points of T' = t. This line is drawn lightly through those values of T' for which the index correction is known.

The values of (T' - t) computed as mentioned above, are then laid off as points measured from the zero-correction line along the appropriate T' lines, one near the upper edge and one near the lower edge of the graph. These points are laid off in both directions from the zero-correction line since the correction may have either sign. Straight lines approximately parallel to the zero-correction line, representing lines of equal temperature-difference correction, are then drawn lightly through those values of T' for which the index correction is known. The graph would now be complete if there were no index corrections, but the lines must be shifted either to the right or to the left at all values of T' where the index correction is not zero. Thus, if at 0° the index correction is +0°01, the zero-correction line as well as all the other correction lines at T' = 0° are shifted one line (or 0°01 correction) to the right. When these shifts have been made to accommodate all known index corrections, the resulting graph consists of a number of zigzag lines, all approximately parallel and having an approximade 45°-trend. The correction lines exterior to the required range of T' and t may now be cut off and the graph is ready for use. A specimen correction graph is shown in figure 1.

As described above, the lines of equal correction for temperature difference between reversal and reading are assumed to be straight. As this assumption is not exactly true, an error is introduced. This error is greater, the greater the interval between the two values of T' for which the points are computed, and is greater, the greater the numerical value of (T' - t). As an example of the magnitude of this error, let us take a graph for a thermometer whose range is 0° to +20° C and prepared for a maximum value of t = 30° C. In this case the maximum error in the graph will occur in the neighborhood of T' = 10° and t = 30° where the error will be approximately 0.003° C. Such an error is not usually significant, but if greater accuracy is desired the values of (T' - t) can be computed for intervening values of T', thus breaking the single straight lines into two or more parts. Because of the increased labor required in this procedure and the small magnitude of the error involved, the refinement is not recommended.

In the case of unprotected thermometers, where C is again the temperature-difference correction

$$(T_W - t) = \frac{CK}{(T' + v_O)}$$

As with the protected thermometers, the temperature difference (T_W - t) is evaluated for a series of C which is varied in steps of 0°01 and the computations carried through for two extreme values of T'. Now, however, a plot of (T_W - t) against T' is to be prepared but is carried out in much the same manner as the previously described plot of T' against t, the index correction shifts being made as before.

Having determined the corrected readings of a protected thermometer and its accompanying unprotected thermometer, the depth at which they were reversed can be computed from the formula

$$D = \frac{(T_u - T)}{Q\rho_m}$$

where D is the depth in meters, T_u is the corrected reading of the unprotected thermometer, T is the true temperature given by the corrected reading of the protected thermometer, Q is the pressure constant of the unprotected thermometer or the change in number of degrees in the corrected reading of the unprotected thermometer produced by a change in pressure of one-tenth kilogram per square centimeter, and ρ_m is the mean specific gravity of the water column above the thermometers when they were reversed. The constant Q is of the order of magnitude of 0.01 and is given in the thermometer certificate, usually in the form of the degrees change in reading per kilogram per square centimeter change in pressure.

The approximate depth of the various water bottles and thermometers will be known from the wire angle and the readings of the meter wheel. From the corrected temperatures and the salinity measurements, the density (σ_t) of the water samples can be determined from Knudsen's "Hydrographical tables." Knowing these values, the values of density in situ (σ_{tD}) are determined by applying three corrections, each of which is given in tabular form in Hesselberg and Sverdrup's paper in Bergens Museums Aarbok, 1914-1915. The most important of these corrections is a function of depth, and since the exact depth of the samples is unknown the resulting values of density in situ will be only approximate. These values are then plotted against their approximate depths, a curve drawn, and a value of the mean density scaled from the curve at half the approximate depth. It is to be remembered that this density-depth chart is constructed solely for the purpose of determining a mean density which is to be used as a factor in the reduction of thermometer depths. It is only necessary to determine this mean density to the nearest unit in the third decimal place; for example, to know that the mean density is 1.034 rather than 1.033 or 1.035. In terms of σ_{tD} this would mean the nearest unit. As the order of magnitude of depth variation of σ_{tD} is about one unit per 200 meters, it is easily seen that the density-depth curve need not be very accurate. After the adjusted depths of the samples have been determined in this manner, and the vertical distribution curves of salinity and temperature have been drawn, these may be

scaled for salinity and temperature at selected depths and values of σ_{tD} computed for these depths. The values of σ_{tD} so derived may then be used to construct a more accurate density-depth curve which can be used to check the values of mean density used in the reduction of the thermometer depths. If the values do not check within the limits mentioned above, a second approximation must be made, but this will rarely be necessary.

From the foregoing it will be seen that one meter in depth corresponds to a difference of about $0.^{\circ}01$ C between the corrected readings of the protected and unprotected thermometers. Experience has shown that unprotected thermometers having a range of about 60° C divided into 1/5° can be read with an accuracy of better than $0.^{\circ}01$. Comparisons of thermometer depths with depths determined by wire length when the wire angle was small indicate that the method gives depths reliable to within about ±10 meters. The use of unprotected thermometers at intervals along the length of a wire to which a number of water bottles is attached, in conjunction with meter-wheel readings, thus provides a satisfactory method of determining the depths of all the water bottles on the wire.

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FIG. I.—GRAPH SHOWING CORRECTIONS FOR PROTECTED DEEP-SEA REVERSING THERMOMETERS BASED ON $(T'-t) = \dfrac{CK^2}{(T'+v_0+K)(T'+v_0)} - \dfrac{C^2K^4}{(T'+v_0+K)^3(T'+v_0)^2}$ FOR $v_0=95°$ AND JENA GLASS 59$^{\text{III}}$ FOR WHICH K=6100

ASSUMING VALUES OF READINGS MAIN THERMOMETERS, T', AND OF INDEX CORRECTIONS, I, AS FOLLOWS:

T'	0°	6°	12°	18°	24°	30°
I	0.00	0.00	+0.02	+0.01	0.00	-0.01

22
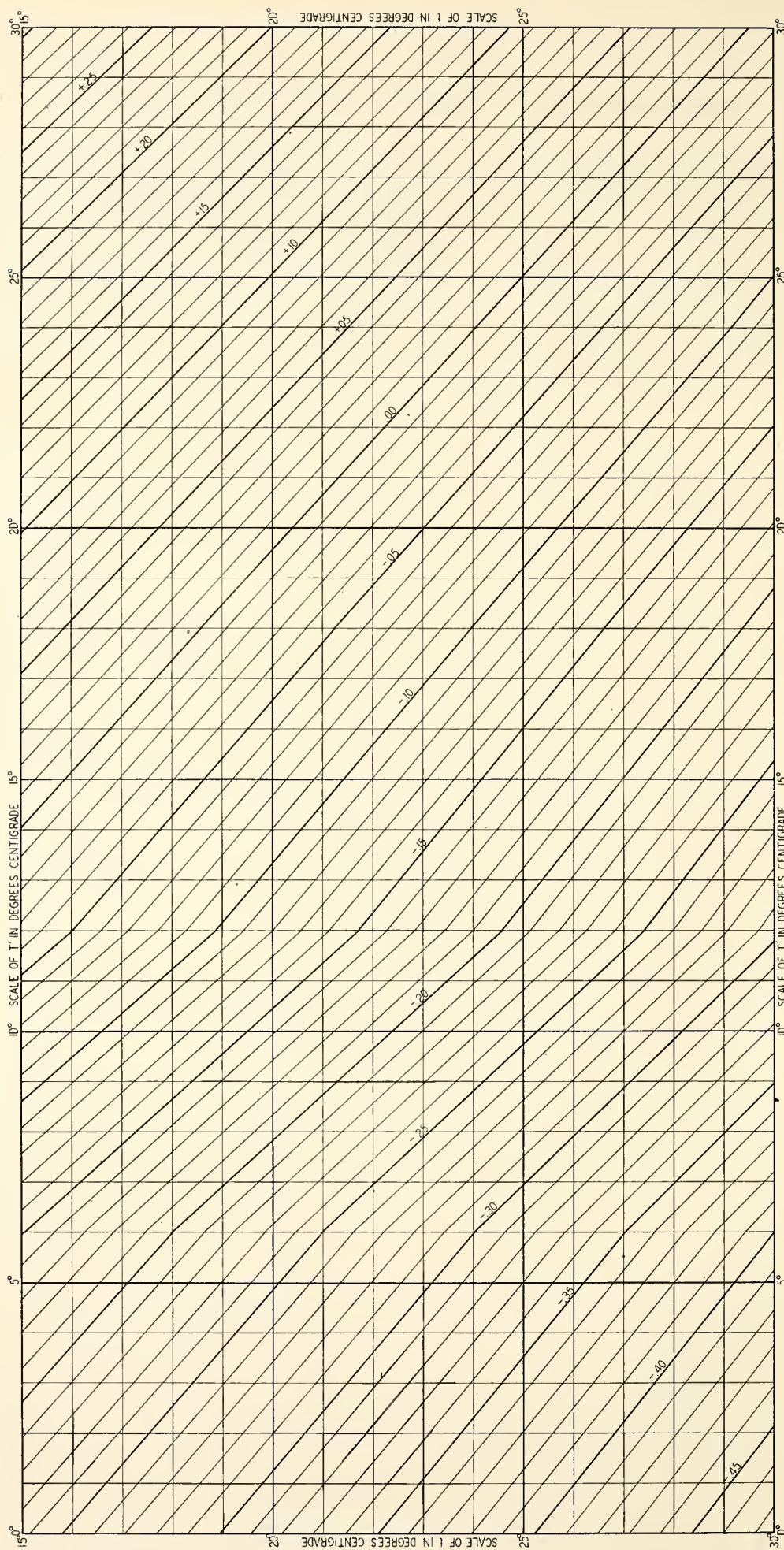
NOTE ON COMPUTATION OF DENSITY OF SEA WATER AND ON

CORRECTIONS FOR DEEP-SEA REVERSING THERMOMETERS

In the reductions of the oceanographic observations made on board the Carnegie during her seventh cruise, it was found necessary to devise methods by which the great amount of computational work involved might be simplified and reduced.

A considerable part of this work was the determination of the density of sea water from its values of salinity and temperature, for which purpose special tables were prepared in the Department of Terrestrial Magnetism.

Table 1 is a table prepared for computing the density, σ_t, being based on the formula

$$\sigma_t = \Sigma_t + (\sigma_0 + 0.1324) \left[1 - A_t + B_t (\sigma_0 - 0.1324) \right] \quad (1)$$

together with the values of the involved constants as given in Knudsen's "Hydrographical tables."

Experience has proved the table more satisfactory than graphs because of the more or less unwieldy graphs resulting from the scale requirements imposed by the requisite degree of refinement.

Table 2 gives the corrections for depth and temperature and for depth and salinity necessary to reduce the values of density, σ_t, to those in situ, σ_{tD}. It is a modification of the tables of Hesselberg and Sverdrup to the extent that the separate corrections for depth and for temperature of the latter tables have been combined, thus reducing the number of entries from three to two.

A similar modification was made of the Hesselberg and Sverdrup correction tables for computing specific volume and dynamic depth.

The accompanying graph (fig. 1) was devised for determining the corrections for unprotected deep-sea reversing thermometers. It is based on the formula for correction

$$\Delta t = \frac{(T_W + v_0)\,(T' - t)}{K} \quad (2)$$

in which T_W is the recorded temperature of the unprotected thermometer, T' the recorded temperature of main thermometer, t is the recorded temperature (corrected) of auxiliary thermometer, v_0 is the volume of broken-off column of mercury at $0°$, and K the coefficient of expansion of the glass (Jena 59[iii] for the thermometers used on the Carnegie, for which $K = 6100$).

Because of the large number of thermometers used in the Carnegie observations, it was not deemed expedient to use graphs for obtaining the corrections for the protected thermometers, since, because of the different values of v_0, it would have been necessary to construct a graph for each thermometer.

Instead a table, of which table 3 is a specimen sheet, was prepared which covered all the Carnegie values of the tabular arguments and was based on the formula for correction

$$\Delta t = \frac{(T' + v_0)\,(T' - t)}{K} + I + \frac{T' + v_0}{K} \left[\frac{(T' + v_0)\,(T' - t)}{K} + I \right] \quad (3)$$

T' and t denoting, respectively, the recorded temperatures of the main and auxiliary thermometers, I denoting the index correction of the main thermometer, and v_0 and K having the same significance as in equation (2). Making $K = 6100$, equation (3) reduces to

$$\Delta t = 0.000164\,(T' + v_0)\,(T' - t)\,[1 + 0.000164\,(T' + v_0)]$$
$$+ I + 0.000164\,I\,(T' + v_0) \quad (4)$$

The first term of the right-hand member of (4) is represented by the tabular values in table 3, hence Δt = tabular value $+ I + 0.000164\,I\,(T' + v_0)$. The term $0.000164\,I\,(T' + v_0)$, may be considered negligible for well-made thermometers for which I does not exceed $0°.10$.

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t

Tabular values give excess of density over unity in units of fifth decimal: thus for S = 34.2 o/oo and t = 4°.55 C, density is 1.02711

Temperature, t	Salinity, S, in o/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
-2.00	2739	2747	2755	2763	2772	2780	2789	2797	2804	2812	2820
-1.95	39	47	55	63	71	80	88	96	04	12	20
-1.90	39	47	55	63	71	79	87	96	04	12	20
-1.85	39	47	55	63	71	79	87	95	04	12	20
-1.80	39	47	55	63	71	79	87	95	03	12	20
-1.75	38	46	55	63	71	79	87	95	03	11	19
-1.70	38	46	54	63	71	79	87	95	03	11	19
-1.65	38	46	54	62	71	79	87	95	03	11	19
-1.60	38	46	54	62	70	78	87	95	03	11	19
-1.55	38	46	54	62	70	78	86	95	03	11	19
-1.50	2738	2746	2754	2762	2770	2778	2786	2794	2802	2811	2819
-1.45	38	46	54	62	70	78	86	94	02	10	19
-1.40	37	46	54	62	70	78	86	94	02	10	18
-1.35	37	45	53	62	70	78	86	94	02	10	18
-1.30	37	45	53	61	69	78	86	94	02	10	18
-1.25	37	45	53	61	69	77	86	94	02	10	18
-1.20	37	45	53	61	69	77	85	93	02	10	18
-1.15	37	45	53	61	69	77	85	93	01	09	18
-1.10	37	45	53	61	69	77	85	93	01	09	17
-1.05	36	45	53	61	69	77	85	93	01	09	17
-1.00	2736	2744	2752	2761	2769	2777	2785	2793	2801	2809	2817
-0.95	36	44	52	60	68	76	85	93	01	09	17
-0.90	36	44	52	60	68	76	84	92	00	09	17
-0.85	36	44	52	60	68	76	84	92	00	08	16
-0.80	35	43	52	60	68	76	84	92	00	08	16
-0.75	35	43	51	59	67	76	84	92	00	08	16
-0.70	35	43	51	59	67	75	83	91	00	08	16
-0.65	35	43	51	59	67	75	83	91	2799	07	15
-0.60	35	43	51	59	67	75	83	91	99	07	15
-0.55	35	42	51	59	67	75	83	91	99	07	15
-0.50	2734	2742	2750	2758	2766	2774	2783	2791	2799	2807	2815
-0.45	34	42	50	58	66	74	82	90	98	07	15
-0.40	34	42	50	58	66	74	82	90	98	06	14
-0.35	34	42	50	58	66	74	82	90	98	06	14
-0.30	33	41	49	57	66	74	82	90	98	06	14
-0.25	33	41	49	57	65	73	81	89	98	06	14
-0.20	33	41	49	57	65	73	81	89	97	05	13
-0.15	33	41	49	57	65	73	81	89	97	05	13
-0.10	32	40	49	57	65	73	81	89	97	05	13
-0.05	32	40	48	56	64	72	81	89	97	05	13
0.00	2732	2740	2748	2756	2764	2772	2780	2788	2796	2805	2813
0.05	32	40	48	56	64	72	80	88	96	04	12
0.10	31	39	48	56	64	72	80	88	96	04	12
0.15	31	39	47	55	63	71	79	87	96	04	12
0.20	31	39	47	55	63	71	79	87	95	03	11
0.25	31	39	47	55	63	71	79	87	95	03	11
0.30	30	38	46	54	62	71	79	87	95	03	11
0.35	30	38	46	54	62	70	78	86	94	02	10
0.40	30	38	46	54	62	70	78	86	94	02	10
0.45	29	37	46	54	62	70	78	86	94	02	10
0.50	2729	2737	2745	2753	2761	2770	2777	2785	2793	2802	2810
0.55	29	37	45	53	61	69	77	85	93	01	09
0.60	29	37	45	53	61	69	77	85	93	01	09
0.65	28	36	44	52	60	69	77	85	93	01	09
0.70	28	36	44	52	60	68	76	84	92	00	08
0.75	28	36	44	52	60	68	76	84	92	00	08
0.80	27	35	43	51	59	68	76	84	92	00	08
0.85	27	35	43	51	59	67	75	83	91	2799	08
0.90	27	35	43	51	59	67	75	83	91	99	07
0.95	27	35	43	51	59	67	75	83	91	99	07
1.00	2726	2734	2742	2750	2758	2766	2774	2783	2791	2799	2807
1.05	26	34	42	50	58	66	74	82	90	98	06
1.10	26	34	42	50	58	66	74	82	90	98	06
1.15	25	33	41	49	57	65	73	81	89	97	06
1.20	25	33	41	49	57	65	73	81	89	97	05

Table 1. For computing density, σ, of sea water for various values of salinity, S,
and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
1.25	2725	2733	2741	2749	2757	2765	2773	2781	2789	2797	2805
1.30	24	32	40	48	56	64	72	80	88	96	04
1.35	24	32	40	48	56	64	72	80	88	96	04
1.40	23	32	40	48	56	64	72	80	88	96	04
1.45	23	31	39	47	55	63	71	79	87	95	03
1.50	2723	2731	2739	2747	2755	2763	2771	2779	2787	2795	2803
1.55	22	30	38	46	54	63	71	79	87	95	03
1.60	22	30	38	46	54	62	70	78	86	94	02
1.65	22	30	38	46	54	62	70	78	86	94	02
1.70	21	29	37	45	53	61	69	77	85	93	01
1.75	21	29	37	45	53	61	69	77	85	93	01
1.80	21	29	37	45	53	61	69	77	85	93	01
1.85	20	28	36	44	52	60	68	76	84	92	00
1.90	20	28	36	44	52	60	68	76	84	92	00
1.95	20	28	36	44	52	60	68	76	84	92	00
2.00	2719	2727	2735	2743	2751	2759	2767	2775	2783	2791	2799
2.05	19	27	35	43	51	59	67	75	83	91	99
2.10	18	26	34	42	50	58	66	74	82	90	98
2.15	18	26	34	42	50	58	66	74	82	90	98
2.20	18	26	34	42	50	58	66	74	82	90	98
2.25	17	25	33	41	49	57	65	73	81	89	97
2.30	17	25	33	41	49	57	65	73	81	89	97
2.35	16	24	32	40	48	56	64	72	80	88	96
2.40	16	24	32	40	48	56	64	72	80	88	96
2.45	15	23	31	39	47	55	63	71	79	87	95
2.50	2715	2723	2731	2739	2747	2755	2763	2771	2779	2787	2795
2.55	15	23	31	39	47	55	63	71	79	87	95
2.60	14	22	30	38	46	54	62	70	78	86	94
2.65	14	22	30	38	46	54	62	70	78	86	94
2.70	13	21	29	37	45	53	61	69	77	85	93
2.75	13	21	29	37	45	53	61	69	77	85	93
2.80	13	21	29	37	44	52	60	68	76	84	92
2.85	12	20	28	36	44	52	60	68	76	84	92
2.90	12	20	28	36	44	52	60	68	76	84	91
2.95	11	19	27	35	43	51	59	67	75	83	91
3.00	2711	2719	2727	2735	2743	2751	2759	2767	2775	2783	2791
3.05	10	18	26	34	42	50	58	66	74	82	90
3.10	10	18	26	34	42	50	58	66	74	82	90
3.15	09	17	25	33	41	49	57	65	73	81	89
3.20	09	17	25	33	41	49	57	65	73	81	89
3.25	08	16	24	32	40	48	56	64	72	80	88
3.30	08	16	24	32	40	48	56	64	72	80	88
3.35	08	15	23	31	39	47	55	63	71	79	87
3.40	07	15	23	31	39	47	55	63	71	79	87
3.45	07	14	22	30	38	46	54	62	70	78	86
3.50	2706	2714	2722	2730	2738	2746	2754	2762	2770	2778	2786
3.55	06	14	22	29	37	45	53	61	69	77	85
3.60	05	13	21	29	37	45	53	61	69	77	85
3.65	05	13	21	29	36	44	52	60	68	76	84
3.70	04	12	20	28	36	44	52	60	68	76	84
3.75	04	12	20	28	35	43	51	59	67	75	83
3.80	03	11	19	27	35	43	51	59	67	75	83
3.85	03	11	19	27	35	42	50	58	66	74	82
3.90	02	10	18	26	34	42	50	58	66	74	82
3.95	02	10	18	26	34	41	49	57	65	73	81
4.00	2701	2709	2717	2725	2733	2741	2749	2757	2765	2773	2781
4.05	01	09	17	25	33	40	48	56	64	72	80
4.10	00	08	16	24	32	40	48	56	64	72	80
4.15	00	08	16	23	31	39	47	55	63	71	79
4.20	2699	07	15	23	31	39	47	55	63	71	79
4.25	99	07	14	22	30	38	46	54	62	70	78
4.30	98	06	14	22	30	38	46	54	62	69	77
4.35	97	05	13	21	29	37	45	53	61	69	77
4.40	97	05	13	21	29	37	45	52	60	68	76
4.45	96	04	12	20	28	36	44	52	60	68	76

Table 1. For computing density, σ, of sea water for various values of salinity, S,
and of temperature, t--Continued

Tempera-ture, t	Salinity, S, in º/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
4.50	2696	2704	2712	2720	2728	2736	2743	2751	2759	2767	2775
4.55	95	03	11	19	27	35	43	51	59	67	75
4.60	95	03	11	19	26	34	42	50	58	66	74
4.65	94	02	10	18	26	34	42	50	58	66	74
4.70	94	02	10	17	25	33	41	49	57	65	73
4.75	93	01	09	17	25	33	41	49	57	64	72
4.80	93	01	08	16	24	32	40	48	56	64	72
4.85	92	00	08	16	24	32	40	48	55	63	71
4.90	92	2699	07	15	23	31	39	47	55	63	71
4.95	91	99	07	15	23	31	38	46	54	62	70
5.00	2690	2698	2706	2714	2722	2730	2738	2746	2754	2762	2770
5.05	90	98	06	14	22	29	37	45	53	61	69
5.10	89	97	05	13	21	29	37	45	53	60	68
5.15	89	97	04	12	20	28	36	44	52	60	68
5.20	88	96	04	12	20	28	36	43	51	59	67
5.25	87	95	03	11	19	27	35	43	51	59	67
5.30	87	95	03	11	18	26	34	42	50	58	66
5.35	86	94	02	10	18	26	34	42	50	57	65
5.40	86	94	01	09	17	25	33	41	49	57	65
5.45	85	93	01	09	17	25	32	40	48	56	64
5.50	2684	2692	2700	2708	2716	2724	2732	2740	2748	2756	2763
5.55	84	92	00	08	15	23	31	39	47	55	63
5.60	83	91	2699	07	15	23	31	39	46	54	62
5.65	83	91	98	06	14	22	30	38	46	54	62
5.70	82	90	98	06	14	22	29	37	45	53	61
5.75	81	89	97	05	13	21	29	37	45	53	60
5.80	81	89	97	05	12	20	28	36	44	52	60
5.85	80	88	96	04	12	20	28	35	43	51	59
5.90	80	87	95	03	11	19	27	35	43	51	59
5.95	79	87	95	03	11	18	26	34	42	50	58
6.00	2678	2686	2694	2702	2710	2718	2726	2734	2742	2749	2757
6.05	78	86	94	01	09	17	25	33	41	49	57
6.10	77	85	93	01	09	17	24	32	40	48	56
6.15	76	84	92	00	08	16	24	32	40	47	55
6.20	76	84	92	2699	07	15	23	31	39	47	55
6.25	75	83	91	99	07	15	22	30	38	46	54
6.30	74	82	90	98	06	14	22	30	38	45	53
6.35	74	82	90	97	05	13	21	29	37	45	53
6.40	73	81	89	97	05	13	20	28	36	44	52
6.45	72	80	88	96	04	12	20	28	36	43	51
6.50	2772	2680	2688	2695	2703	2711	2719	2727	2735	2743	2751
6.55	71	79	87	95	03	11	18	26	34	42	50
6.60	70	78	86	94	02	10	18	26	34	41	49
6.65	70	78	86	93	01	09	17	25	33	41	49
6.70	69	77	85	93	01	09	16	24	32	40	48
6.75	69	76	84	92	00	07	16	24	32	39	47
6.80	68	76	84	91	2699	07	15	23	31	39	47
6.85	67	75	83	91	99	06	14	22	30	38	46
6.90	67	74	82	90	98	05	14	22	30	31	45
6.95	66	74	82	89	97	05	13	21	29	37	45
7.00	2665	2673	2681	2689	2697	2705	2712	2720	2728	2736	2744
7.05	64	72	80	88	96	04	12	20	27	35	43
7.10	64	72	80	87	95	03	11	19	27	35	42
7.15	63	71	79	87	95	02	10	18	26	34	42
7.20	62	70	78	86	94	02	10	17	25	33	41
7.25	62	70	77	85	93	01	09	17	25	32	40
7.30	61	69	77	85	92	00	08	16	24	32	40
7.35	60	68	76	84	92	00	07	15	23	31	39
7.40	60	67	75	83	91	2699	07	15	22	30	38
7.45	59	67	74	82	90	98	06	14	22	29	37
7.50	2658	2666	2674	2682	2689	2697	2705	2713	2721	2729	2737
7.55	57	65	73	81	89	97	04	12	20	28	36
7.60	57	64	72	80	88	96	04	12	19	27	35
7.65	56	64	72	79	87	95	03	11	19	27	34
7.70	55	63	71	79	87	94	02	10	18	26	34
7.75	54	62	70	78	86	94	02	09	17	25	33
7.80	54	62	69	77	85	93	01	09	17	24	32
7.85	53	61	69	77	84	92	00	08	15	24	32
7.90	52	60	68	76	84	92	2699	07	15	23	31
7.95	52	59	67	75	83	91	99	07	14	22	30

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-perature, t	Salinity, S, in º/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
8.00	2651	2659	2667	2674	2682	2690	2698	2706	2714	2722	2729
8.05	50	58	66	74	82	89	97	05	13	21	29
8.10	49	57	65	73	81	89	96	04	12	20	28
8.15	49	56	64	72	80	88	96	03	11	19	27
8.20	48	56	64	71	79	87	95	03	11	18	26
8.25	47	55	63	71	78	86	94	02	10	18	26
8.30	46	54	62	70	78	85	93	01	09	17	25
8.35	46	53	61	69	77	85	93	00	08	16	24
8.40	45	53	60	68	76	84	92	00	07	15	23
8.45	44	52	60	68	75	83	91	2649	07	15	22
8.50	2643	2651	2659	2667	2675	2682	2690	2698	2706	2714	2722
8.55	42	50	58	66	74	82	89	97	05	13	21
8.60	42	50	57	65	73	81	89	97	04	12	20
8.65	41	49	57	64	72	80	88	96	04	11	19
8.70	40	48	56	64	71	79	87	95	03	11	18
8.75	39	47	55	63	71	79	86	94	02	10	18
8.80	39	46	54	62	70	78	86	93	01	09	17
8.85	38	46	54	61	69	77	85	93	01	08	16
8.90	37	45	53	61	68	76	84	92	00	07	15
8.95	36	44	52	60	68	75	83	91	2699	07	15
9.00	2636	2643	2651	2659	2667	2675	2682	2690	2698	2706	2714
9.05	35	43	50	58	66	74	82	89	97	05	13
9.10	34	42	50	57	65	73	81	89	96	04	12
9.15	33	41	49	57	64	72	80	88	96	03	11
9.20	32	40	48	56	64	71	79	87	95	03	10
9.25	31	39	47	55	63	71	78	86	94	02	10
9.30	31	38	46	54	62	70	77	85	93	01	09
9.35	30	38	45	53	61	69	77	84	92	00	08
9.40	29	37	45	52	60	68	76	84	91	2699	07
9.45	28	36	44	52	59	67	75	83	91	98	06
9.50	2627	2635	2643	2651	2659	2666	2674	2682	2690	2698	2705
9.55	27	34	42	50	58	66	73	81	89	97	05
9.60	26	33	41	49	57	65	73	80	88	96	04
9.65	25	33	40	48	56	64	72	80	87	95	03
9.70	24	32	40	47	55	63	71	79	86	94	02
9.75	23	31	39	47	54	62	70	78	86	93	01
9.80	22	30	38	46	54	61	69	77	85	93	00
9.85	22	29	37	45	53	61	68	76	84	92	00
9.90	21	29	36	44	52	60	68	75	83	91	2699
9.95	20	28	36	43	51	59	67	75	82	90	98
10.00	2619	2627	2635	2643	2650	2658	2666	2674	2681	2689	2697
10.05	18	26	34	42	49	57	65	73	81	88	96
10.10	17	25	33	41	49	56	64	72	80	88	95
10.15	16	24	32	40	48	55	63	71	79	87	94
10.20	16	23	31	39	47	55	62	70	78	86	94
10.25	15	23	30	38	46	54	62	69	77	85	93
10.30	14	22	29	37	45	53	61	68	76	84	92
10.35	13	21	29	36	44	52	60	68	75	83	91
10.40	12	20	28	36	43	51	59	67	74	82	90
10.45	11	19	27	35	42	50	58	66	74	81	89
10.50	2610	2618	2626	2634	2642	2649	2657	2665	2673	2680	2688
10.55	09	17	25	33	41	48	56	64	72	80	87
10.60	09	16	24	32	40	48	55	63	71	79	86
10.65	08	16	23	31	39	47	54	62	70	78	86
10.70	07	15	22	30	38	46	54	61	69	77	85
10.75	06	14	22	29	37	45	53	61	68	76	84
10.80	05	13	21	28	36	44	52	60	67	75	83
10.85	04	12	20	28	35	43	51	59	67	74	82
10.90	03	11	19	27	35	42	50	58	66	73	81
10.95	02	10	18	26	34	41	49	57	65	72	80
11.00	2602	2609	2617	2625	2633	2641	2648	2656	2664	2672	2679
11.05	01	08	16	24	32	40	47	55	63	71	78
11.10	00	08	15	23	31	39	46	54	62	70	78
11.15	2599	07	14	22	30	38	46	53	61	69	77
11.20	98	06	14	21	29	37	45	52	60	68	76
11.25	97	05	13	20	28	36	44	51	59	67	75
11.30	96	04	12	19	27	35	43	51	58	66	74
11.35	95	03	11	18	26	34	42	50	57	65	73
11.40	94	02	10	18	25	33	41	49	56	64	72
11.45	93	01	09	17	24	32	40	48	55	63	71

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem- pera- ture, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
11.50	2592	2600	2608	2616	2623	2631	2639	2647	2655	2662	2670
11.55	92	2599	07	15	23	30	38	46	54	61	69
11.60	91	98	06	14	22	29	37	45	53	60	68
11.65	90	97	05	13	21	28	36	44	52	60	67
11.70	89	96	04	12	20	28	35	43	51	59	66
11.75	88	96	03	11	19	27	34	42	50	58	65
11.80	87	95	02	10	18	26	33	41	49	57	64
11.85	86	94	01	09	17	25	32	40	48	56	64
11.90	85	93	01	08	16	24	32	39	47	55	63
11.95	84	92	00	07	15	23	31	38	46	54	62
12.00	2583	2591	2599	2606	2614	2622	2630	2637	2645	2653	2661
12.05	82	90	98	05	13	21	29	37	44	52	60
12.10	81	89	97	05	12	20	28	36	43	51	59
12.15	80	88	96	04	11	19	27	35	42	50	58
12.20	79	87	95	03	10	18	26	34	41	49	57
12.25	78	86	94	02	09	17	25	33	40	48	56
12.30	77	85	93	01	08	16	24	32	39	47	55
12.35	76	84	92	00	07	15	23	31	38	46	54
12.40	75	83	91	2599	06	14	22	30	37	45	53
12.45	74	82	90	98	05	13	21	29	36	44	52
12.50	2573	2581	2589	2597	2604	2612	2620	2628	2635	2643	2651
12.55	73	80	88	96	03	11	19	27	34	42	50
12.60	72	79	87	95	02	10	18	26	33	41	49
12.65	71	78	86	94	02	09	17	25	32	40	48
12.70	70	77	85	93	01	08	16	24	32	39	47
12.75	69	76	84	92	00	07	15	23	31	38	46
12.80	68	75	83	91	2599	06	14	22	30	37	45
12.85	67	74	82	90	98	05	13	21	29	36	44
12.90	66	73	81	89	97	04	12	20	28	35	43
12.95	65	72	80	88	96	03	11	19	27	34	42
13.00	2564	2571	2579	2587	2595	2602	2610	2618	2626	2633	2641
13.05	63	70	78	86	94	01	09	17	25	32	40
13.10	62	69	77	85	93	00	08	16	24	31	39
13.15	61	68	76	84	92	2599	07	15	23	30	38
13.20	60	67	75	83	91	98	06	14	22	29	37
13.25	59	66	74	82	90	97	05	13	20	28	36
13.30	58	65	73	81	89	96	04	12	19	27	35
13.35	57	64	72	80	88	95	03	11	18	26	34
13.40	56	63	71	79	86	94	02	10	17	25	33
13.45	55	62	70	78	85	93	01	09	16	24	32
13.50	2554	2561	2569	2577	2584	2592	2600	2608	2615	2623	2631
13.55	53	60	68	76	83	91	2599	07	14	22	30
13.60	52	59	67	75	82	90	98	06	13	21	29
13.65	51	58	66	74	81	89	97	05	12	20	28
13.70	49	57	65	73	80	88	96	04	11	19	27
13.75	48	56	64	72	79	87	95	03	10	18	26
13.80	47	55	63	71	78	86	94	01	09	17	25
13.85	46	54	62	70	77	85	93	00	08	16	24
13.90	45	53	61	69	76	84	92	2599	07	15	23
13.95	44	52	60	68	75	83	91	98	06	14	22
14.00	2543	2551	2559	2567	2574	2582	2590	2597	2605	2613	2620
14.05	42	50	58	65	73	81	89	96	04	12	19
14.10	41	49	57	64	72	80	88	95	03	11	18
14.15	40	48	56	63	71	79	86	94	02	10	17
14.20	39	47	55	62	70	78	85	93	01	08	16
14.25	38	46	53	61	69	77	84	92	00	07	15
14.30	37	45	52	60	68	76	83	91	2599	06	14
14.35	36	44	51	59	67	74	82	90	98	05	13
14.40	35	43	50	58	66	73	81	89	96	04	12
14.45	34	41	49	57	65	72	80	88	95	03	11
14.50	2533	2540	2548	2556	2564	2571	2579	2587	2594	2602	2610
14.55	32	39	47	55	62	70	78	86	93	01	09
14.60	31	38	46	54	61	69	77	84	92	00	08
14.65	29	37	45	53	60	68	76	83	91	2599	07
14.70	28	36	44	52	59	67	75	82	90	98	05
14.75	27	35	43	50	58	66	74	81	89	97	04
14.80	26	34	42	49	57	65	72	80	88	96	03
14.85	25	33	41	48	56	64	71	79	87	95	02
14.90	24	32	40	47	55	63	70	78	86	93	01
14.95	23	31	38	46	54	62	69	77	85	92	00

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-° pera- ture, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
15.00	2522	2530	2537	2545	2553	2561	2568	2576	2584	2591	2599
15.05	21	29	36	44	52	59	67	75	82	90	98
15.10	20	28	35	43	51	58	66	74	81	89	97
15.15	19	26	34	42	49	57	65	73	80	88	96
15.20	18	25	33	41	48	56	64	71	79	87	95
15.25	16	24	32	40	47	55	63	70	78	86	93
15.30	15	23	31	38	46	54	62	69	77	85	92
15.35	14	22	30	37	45	53	60	68	76	83	91
15.40	13	21	29	36	44	52	59	67	75	82	90
15.45	12	20	27	35	43	50	58	66	74	81	89
15.50	2511	2519	2526	2534	2542	2549	2557	2565	2572	2580	2588
15.55	10	17	25	33	41	48	56	64	71	79	87
15.60	09	16	24	32	39	47	55	63	70	78	86
15.65	08	15	23	31	38	46	54	61	69	77	84
15.70	06	14	22	30	37	45	53	60	68	76	83
15.75	05	13	21	28	36	44	51	59	67	74	82
15.80	04	12	20	27	35	43	50	58	66	73	81
15.85	03	11	18	26	34	42	49	57	65	72	80
15.90	02	10	17	25	33	40	48	56	63	71	79
15.95	01	09	16	24	32	39	47	55	62	70	78
16.00	2500	2507	2515	2523	2530	2538	2546	2554	2561	2569	2577
16.05	2499	06	14	22	29	37	45	52	60	68	75
16.10	97	05	13	20	28	36	44	51	59	67	74
16.15	96	04	12	19	27	35	42	50	58	65	73
16.20	95	03	11	18	26	34	41	49	57	64	72
16.25	94	02	09	17	25	32	40	48	55	63	71
16.30	93	01	08	16	24	31	39	47	54	62	70
16.35	92	2499	07	15	22	30	38	45	53	61	68
16.40	91	98	06	14	21	29	37	44	52	60	67
16.45	89	97	05	12	20	28	35	43	51	58	66
16.50	2488	2496	2504	2511	2519	2527	2534	2542	2550	2557	2565
16.55	87	95	02	10	18	25	33	41	48	56	64
16.60	86	94	01	09	17	24	32	40	47	55	63
16.65	85	92	00	08	15	23	31	38	46	54	61
16.70	84	91	2499	07	14	22	30	37	45	53	60
16.75	82	90	98	05	13	21	28	36	44	51	59
16.80	81	89	97	04	12	20	27	35	43	50	58
16.85	80	88	95	03	11	18	26	34	41	49	57
16.90	79	87	94	02	10	17	25	33	40	48	56
16.95	78	85	93	01	08	16	24	31	39	47	54
17.00	2477	2484	2492	2500	2507	2515	2523	2530	2538	2546	2553
17.05	75	83	91	2498	06	14	21	29	37	44	52
17.10	74	82	90	97	05	13	20	28	35	43	51
17.15	73	81	88	96	04	11	19	27	34	42	50
17.20	72	79	87	95	02	10	18	25	33	41	48
17.25	71	78	86	94	01	09	17	24	32	40	47
17.30	69	77	85	92	00	08	15	23	31	38	46
17.35	68	76	83	91	2499	06	14	22	29	37	45
17.40	67	75	82	90	98	05	13	21	28	36	44
17.45	66	74	81	89	96	04	12	19	27	35	42
17.50	2465	2472	2480	2488	2495	2503	2511	2518	2526	2533	2541
17.55	63	71	79	86	94	02	09	17	25	32	40
17.60	62	70	78	85	93	00	08	16	23	31	39
17.65	61	69	76	84	92	2499	07	15	22	30	37
17.70	60	67	75	83	90	98	06	13	21	29	36
17.75	59	66	74	82	89	97	05	12	20	27	35
17.80	57	65	73	80	88	96	03	11	19	26	34
17.85	56	64	71	79	87	94	02	10	17	25	33
17.90	55	63	70	78	86	93	01	09	16	24	31
17.95	54	62	69	77	84	92	00	07	15	23	30
18.00	2453	2460	2468	2476	2483	2491	2498	2506	2514	2521	2529
18.05	51	59	67	74	82	90	97	05	13	20	28
18.10	50	58	65	73	81	88	96	04	11	19	27
18.15	49	57	64	72	79	87	95	02	10	18	25
18.20	48	55	63	71	78	86	93	01	09	16	24
18.25	46	54	62	69	77	85	92	00	08	15	23
18.30	45	53	60	68	76	83	91	2499	06	14	22
18.35	44	52	59	67	74	82	90	97	05	13	20
18.40	43	50	58	66	73	81	88	96	04	11	19
18.45	41	49	57	64	72	80	87	95	03	10	18

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Temperature, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
18.50	2440	2448	2455	2463	2471	2478	2486	2494	2501	2509	2516
18.55	39	47	54	62	69	77	85	92	00	08	15
18.60	38	45	53	61	68	76	83	91	2499	06	14
18.65	36	44	52	59	67	75	82	90	97	05	13
18.70	35	43	50	58	66	73	81	89	96	04	11
18.75	34	42	49	57	64	72	80	87	95	03	10
18.80	33	40	48	56	63	71	78	86	94	01	09
18.85	31	39	47	54	62	70	77	85	92	00	08
18.90	30	38	45	53	61	68	76	84	91	2499	06
18.95	29	37	44	52	59	67	75	82	90	98	05
19.00	2428	2435	2443	2451	2458	2466	2473	2481	2489	2496	2504
19.05	26	34	42	49	57	65	72	80	87	95	03
19.10	25	33	40	48	56	63	71	78	86	94	01
19.15	24	31	39	47	54	62	70	77	85	92	00
19.20	23	30	38	45	53	61	68	76	84	91	2499
19.25	21	29	37	44	52	59	67	75	82	90	98
19.30	20	28	35	43	50	58	66	73	81	89	96
19.35	19	26	34	42	49	57	64	72	80	87	95
19.40	17	25	33	40	48	56	63	71	78	86	94
19.45	16	24	31	39	47	54	62	69	77	85	92
19.50	2415	2422	2430	2438	2445	2453	2461	2468	2476	2483	2491
19.55	14	21	29	36	44	52	59	67	75	82	90
19.60	12	20	27	35	43	50	58	66	73	81	88
19.65	11	19	26	34	41	49	57	64	72	79	87
19.70	10	17	25	33	40	48	55	63	71	78	86
19.75	08	16	24	31	39	46	54	62	69	77	85
19.80	07	15	22	30	38	45	53	60	68	76	83
19.85	06	13	21	29	36	44	51	59	67	74	82
19.90	05	12	20	27	35	43	50	58	65	73	81
19.95	03	11	18	26	34	41	49	56	64	72	79
20.00	2402	2410	2417	2425	2432	2440	2448	2455	2463	2470	2478
20.05	01	08	16	23	31	39	46	54	62	69	77
20.10	2399	07	15	22	30	37	45	53	60	68	75
20.15	98	06	13	21	28	36	44	51	59	66	74
20.20	97	04	12	19	27	35	42	50	57	65	73
20.25	95	03	11	18	26	33	41	49	56	64	71
20.30	94	02	09	17	24	32	40	47	55	62	70
20.35	93	00	08	15	23	31	38	46	54	61	69
20.40	91	2399	07	14	22	29	37	45	52	60	67
20.45	90	98	05	13	20	28	36	43	51	58	66
20.50	2389	2396	2404	2411	2419	2427	2434	2442	2449	2457	2465
20.55	87	95	03	10	18	25	33	41	48	56	63
20.60	86	94	01	09	16	24	32	39	47	54	62
20.65	85	92	00	07	15	23	30	38	45	53	61
20.70	83	91	2399	06	14	21	29	37	44	52	59
20.75	82	90	97	05	12	20	28	35	43	50	58
20.80	81	88	96	03	11	19	26	34	41	49	57
20.85	79	87	95	02	10	17	25	33	40	48	55
20.90	78	86	93	01	08	16	24	31	39	46	54
20.95	77	84	92	2399	07	15	22	30	37	45	53
21.00	2375	2383	2391	2398	2406	2413	2421	2429	2436	2444	2451
21.05	74	82	89	97	04	12	20	27	35	42	50
21.10	73	80	88	95	03	11	18	26	33	41	49
21.15	71	79	86	94	02	09	17	24	32	40	47
21.20	70	77	85	93	00	08	15	23	31	38	46
21.25	69	76	84	91	2399	06	14	22	29	37	44
21.30	67	75	82	90	97	05	13	20	28	35	43
21.35	66	73	81	89	96	04	11	19	26	34	42
21.40	64	72	80	87	95	02	10	18	25	33	40
21.45	63	71	78	86	93	01	09	16	24	31	39
21.50	2362	2369	2377	2384	2392	2400	2407	2415	2422	2430	2438
21.55	60	68	75	83	91	2398	06	13	21	29	36
21.60	59	66	74	82	89	97	04	12	20	27	35
21.65	58	65	73	80	88	95	03	11	18	26	33
21.70	56	64	71	79	86	94	02	09	17	24	32
21.75	55	62	70	78	85	93	00	08	15	23	31
21.80	53	61	69	76	84	91	2399	07	14	22	29
21.85	52	60	67	75	82	90	98	05	13	20	28
21.90	51	58	66	73	81	89	96	04	11	19	26
21.95	49	57	64	72	80	87	95	02	10	18	25

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
22.00	2348	2356	2363	2371	2378	2386	2393	2401	2409	2416	2424
22.05	46	54	62	69	77	84	92	00	07	15	22
22.10	45	53	60	68	75	83	91	2398	06	13	21
22.15	44	51	59	66	74	82	89	97	04	12	19
22.20	42	50	57	65	73	80	88	95	03	10	18
22.25	41	48	56	64	71	79	86	94	01	09	17
22.30	39	47	55	62	70	77	85	92	00	08	15
22.35	38	46	53	61	68	76	83	91	2399	06	14
22.40	37	44	52	59	67	75	82	90	97	05	12
22.45	35	43	50	58	65	73	81	88	96	03	11
22.50	2334	2341	2349	2357	2364	2372	2379	2387	2394	2402	2410
22.55	32	40	48	55	63	70	78	85	93	01	08
22.60	31	39	46	54	61	69	76	84	92	2399	07
22.65	30	37	45	52	60	67	75	83	90	97	05
22.70	28	36	43	51	58	66	74	81	89	96	04
22.75	27	34	42	49	57	65	72	80	87	95	02
22.80	25	33	40	48	56	63	71	78	86	93	01
22.85	24	31	39	47	54	62	69	77	84	92	00
22.90	22	30	38	45	53	60	68	75	83	91	2398
22.95	21	29	36	44	51	59	67	74	82	89	97
23.00	2320	2327	2335	2342	2350	2358	2365	2373	2380	2388	2395
23.05	18	26	33	41	48	56	64	71	79	86	94
23.10	17	24	32	39	47	55	62	70	77	85	92
23.15	15	23	30	38	46	53	61	68	76	83	91
23.20	14	21	29	37	44	52	59	67	74	82	90
23.25	12	20	28	35	43	50	58	65	73	80	88
23.30	11	19	26	34	41	49	56	64	71	79	87
23.35	10	17	25	32	40	47	55	62	70	78	85
23.40	08	16	23	31	38	46	53	61	69	76	84
23.45	07	14	22	29	37	44	52	60	67	75	82
23.50	2305	2313	2320	2328	2335	2343	2351	2358	2366	2373	2381
23.55	04	11	19	26	34	41	49	57	64	72	79
23.60	02	10	17	25	32	40	48	55	63	70	78
23.65	01	08	16	23	31	39	46	54	61	69	76
23.70	2299	07	14	22	30	37	45	52	60	67	75
23.75	98	05	13	21	28	36	43	51	58	66	74
23.80	96	04	12	19	27	34	42	49	57	64	72
23.85	95	03	10	18	25	33	40	48	55	63	71
23.90	94	01	09	16	24	31	39	46	54	62	69
23.95	92	00	07	15	22	30	37	45	53	60	68
24.00	2291	2298	2306	2313	2321	2328	2336	2344	2351	2359	2366
24.05	89	97	04	12	19	27	34	42	50	57	65
24.10	88	95	03	10	18	25	33	41	48	56	63
24.15	86	94	01	09	16	24	31	39	47	54	62
24.20	85	92	00	07	15	22	30	38	45	53	60
24.25	83	91	2298	06	13	21	28	36	44	51	59
24.30	82	89	97	04	12	19	27	35	42	50	57
24.35	80	88	95	03	10	18	25	33	41	48	56
24.40	79	86	94	01	09	16	24	32	39	47	54
24.45	77	85	92	00	07	15	22	30	38	45	53
24.50	2276	2283	2291	2298	2306	2313	2321	2329	2336	2344	2351
24.55	74	82	89	97	04	12	19	27	35	42	50
24.60	73	80	88	95	03	10	18	26	33	41	48
24.65	71	79	86	94	01	09	16	24	32	39	47
24.70	70	77	85	92	00	07	15	23	30	38	45
24.75	68	76	83	91	2298	06	13	21	29	36	44
24.80	67	74	82	89	97	04	12	20	27	35	42
24.85	65	73	80	88	95	03	10	18	26	33	41
24.90	64	71	79	86	94	01	09	17	24	32	39
24.95	62	70	77	85	92	00	07	15	23	30	38
25.00	2261	2268	2276	2283	2291	2298	2306	2314	2321	2329	2336
25.05	59	67	74	82	89	97	04	12	20	27	35
25.10	58	65	73	80	88	95	03	10	18	26	33
25.15	56	64	71	79	86	94	01	09	16	24	32
25.20	55	62	70	77	85	92	00	07	15	23	30
25.25	53	61	68	76	83	91	2298	06	13	21	28
25.30	52	59	67	74	82	89	97	04	12	19	27
25.35	50	58	65	73	80	88	95	03	10	18	25
25.40	48	56	64	71	79	86	94	01	09	16	24
25.45	47	54	62	70	77	85	92	00	07	15	22

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
25.50	2245	2253	2261	2268	2276	2283	2291	2298	2306	2313	2321
25.55	44	51	59	67	74	82	89	97	04	12	19
25.60	42	50	57	65	73	80	88	95	03	10	18
25.65	41	48	56	63	71	79	86	94	01	09	16
25.70	39	47	54	62	69	77	85	92	00	07	15
25.75	38	45	53	60	68	75	83	90	2298	06	13
25.80	36	44	51	59	66	74	81	89	97	04	12
25.85	35	42	50	57	65	72	80	87	95	03	10
25.90	33	41	48	56	63	71	78	86	93	01	09
25.95	32	39	47	54	62	69	77	84	92	2299	07
26.00	2230	2238	2245	2253	2260	2268	2275	2283	2290	2298	2305
26.05	29	36	44	51	59	66	74	81	89	96	04
26.10	27	34	42	50	57	65	72	80	87	95	02
26.15	25	33	40	48	55	63	71	78	86	93	01
26.20	24	31	39	46	54	61	69	77	84	92	2299
26.25	22	30	37	45	52	60	67	75	82	90	98
26.30	21	28	36	43	51	58	66	73	81	88	96
26.35	19	27	34	42	49	57	64	72	79	87	94
26.40	18	25	33	40	48	55	63	70	78	85	93
26.45	16	23	31	39	46	54	61	69	76	84	91
26.50	2214	2222	2229	2237	2244	2252	2260	2267	2275	2282	2290
26.55	13	20	28	35	43	50	58	65	73	81	88
26.60	11	19	26	34	41	49	56	64	71	79	87
26.65	10	17	25	32	40	47	55	62	70	77	85
26.70	08	16	23	31	38	46	53	61	68	76	83
26.75	07	14	22	29	37	44	52	59	67	74	82
26.80	05	12	20	28	35	43	50	58	65	73	80
26.85	03	11	18	26	34	41	49	56	64	71	79
26.90	02	09	17	24	32	39	47	54	62	70	77
26.95	00	08	15	23	30	38	45	53	60	68	75
27.00	2199	2206	2214	2221	2229	2236	2244	2251	2259	2266	2274
27.05	97	05	12	20	27	35	42	50	57	65	72
27.10	95	03	10	18	26	33	41	48	56	63	71
27.15	94	01	09	16	24	31	39	46	54	62	69
27.20	92	00	07	15	22	30	37	45	52	60	67
27.25	91	2198	06	13	21	28	36	43	51	58	66
27.30	89	97	04	12	19	27	34	42	49	57	64
27.35	87	95	02	10	17	25	32	40	47	55	63
27.40	86	93	01	08	16	23	31	38	46	53	61
27.45	84	92	2199	07	14	22	29	37	44	52	59
27.50	2183	2190	2198	2205	2213	2220	2228	2235	2243	2250	2258
27.55	81	88	96	03	11	19	26	34	41	49	56
27.60	79	87	94	02	09	17	24	32	39	47	54
27.65	78	85	93	00	08	15	23	30	38	45	53
27.70	76	84	91	2199	06	14	21	29	36	44	51
27.75	74	82	90	97	05	12	20	27	35	42	50
27.80	73	80	88	95	03	10	18	25	33	41	48
27.85	71	79	86	94	01	09	16	24	31	39	46
27.90	70	77	85	92	00	07	15	22	30	37	45
27.95	68	76	83	91	2198	05	13	21	28	36	43
28.00	2166	2174	2181	2189	2196	2204	2212	2219	2227	2234	2242
28.05	65	72	80	87	95	02	10	17	25	32	40
28.10	63	71	78	86	93	01	08	16	23	31	38
28.15	61	69	77	84	92	2199	07	14	22	29	37
28.20	60	67	75	82	90	97	05	12	20	27	35
28.25	58	66	73	81	88	96	03	11	18	26	33
28.30	57	64	72	79	87	94	02	09	17	24	32
28.35	55	62	70	77	85	92	00	07	15	22	30
28.40	53	61	68	76	83	91	2198	06	13	21	28
28.45	52	59	67	74	82	89	97	04	12	19	27
28.50	2150	2157	2165	2172	2180	2187	2195	2202	2210	2218	2225
28.55	48	56	63	71	78	86	93	01	08	16	23
28.60	47	54	62	69	77	84	92	2199	07	14	22
28.65	45	52	60	67	75	83	90	97	05	13	20
28.70	43	51	58	66	73	81	88	96	03	11	18
28.75	42	49	57	64	72	79	87	94	02	09	17
28.80	40	48	55	63	70	78	85	93	00	08	15
28.85	38	46	53	61	68	76	83	91	2198	06	13
28.90	37	44	52	59	67	74	80	89	97	04	12
28.95	35	43	50	58	65	73	80	88	95	03	10

Table 1. For computing density, σ, of sea water for various values of salinity, S,
and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	34.0	34.1	34.2	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.0
°											
29.00	2133	2141	2148	2156	2163	2171	2178	2186	2193	2201	2208
29.05	32	39	47	54	62	69	77	84	92	2199	07
29.10	30	38	45	53	60	68	75	83	90	98	05
29.15	28	36	43	51	58	66	73	81	88	96	03
29.20	27	34	42	49	57	64	72	79	87	94	02
29.25	25	32	40	47	55	63	70	77	85	93	00
29.30	23	31	38	46	53	61	68	76	83	91	2198
29.35	22	29	37	44	52	59	67	74	82	89	97
29.40	20	27	35	42	50	57	65	72	80	87	95
29.45	18	26	33	41	48	56	63	71	78	86	93
29.50	2117	2124	2132	2139	2147	2154	2162	2169	2177	2184	2192
29.55	15	22	30	37	45	52	60	67	75	82	90
29.60	13	21	28	36	43	51	58	66	73	81	88
29.65	11	19	26	34	41	49	56	64	71	79	86
29.70	10	17	25	32	40	47	55	62	70	77	85
29.75	08	16	23	31	38	46	53	61	68	76	83
29.80	06	14	21	29	36	44	51	59	66	74	81
29.85	05	12	20	27	35	42	50	57	65	72	80
29.90	03	11	18	26	33	41	48	56	63	71	78
29.95	01	09	16	24	31	39	46	54	61	69	76
30.00	2100	2107	2115	2122	2130	2137	2145	2152	2160	2167	2175

Tem-pera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°											
-2.00	2820	2828	2837	2845	2853	2861	2869	2877	2885	2893	2902
-1.95	20	28	36	45	53	61	69	77	85	93	01
-1.90	20	28	36	44	52	61	69	77	85	93	01
-1.85	20	28	36	44	52	60	69	77	85	93	01
-1.80	20	28	36	44	52	60	68	76	85	93	01
-1.75	19	28	36	44	52	60	68	76	84	93	01
-1.70	19	27	36	44	52	60	68	76	84	92	00
-1.65	19	27	35	44	52	60	68	76	84	92	00
-1.60	19	27	35	43	51	60	68	76	84	92	00
-1.55	19	27	35	43	51	59	67	76	84	92	00
-1.50	2819	2827	2835	2843	2851	2859	2867	2875	2884	2892	2900
-1.45	19	27	35	43	51	59	67	75	83	92	00
-1.40	18	26	35	43	51	59	67	75	83	91	2899
-1.35	18	26	34	43	51	59	67	75	83	91	99
-1.30	18	26	34	42	50	59	67	75	83	91	99
-1.25	18	26	34	42	50	58	67	75	83	91	99
-1.20	18	26	34	42	50	58	66	74	83	91	99
-1.15	18	26	34	42	50	58	66	74	82	90	99
-1.10	17	25	34	42	50	58	66	74	82	90	98
-1.05	17	25	33	42	50	58	66	74	82	90	98
-1.00	2817	2825	2833	2841	2849	2858	2866	2874	2882	2890	2898
-0.95	17	25	33	41	49	57	65	74	82	90	98
-0.90	17	25	33	41	49	57	65	73	81	89	98
-0.85	16	25	33	41	49	57	65	73	81	89	97
-0.80	16	24	32	40	49	57	65	73	81	89	97
-0.75	16	24	32	40	48	56	64	73	81	89	97
-0.70	16	24	32	40	48	56	64	72	80	88	97
-0.65	15	24	32	40	48	56	64	72	80	88	96
-0.60	15	23	31	40	48	56	64	72	80	88	96
-0.55	15	23	31	39	47	55	64	72	80	88	96
-0.50	2815	2823	2831	2839	2847	2855	2863	2871	2879	2888	2896
-0.45	15	23	31	39	47	55	63	71	79	87	95
-0.40	14	22	31	39	47	55	63	71	79	87	95
-0.35	14	22	30	38	46	54	63	71	79	87	95
-0.30	14	22	30	38	46	54	62	70	78	87	95
-0.25	14	22	30	38	46	54	62	70	78	86	94
-0.20	13	22	30	38	46	54	62	70	78	86	94
-0.15	13	21	29	37	46	54	62	70	78	86	94
-0.10	13	21	29	37	45	53	61	69	78	86	94
-0.05	13	21	29	37	45	53	61	69	77	85	93

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	25.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
° 0.00	2813	2821	2829	2837	2845	2853	2861	2869	2877	2885	2893
0.05	12	20	28	36	44	53	61	69	77	85	93
0.10	12	20	28	36	44	52	60	68	76	84	93
0.15	12	20	28	36	44	52	60	68	76	84	92
0.20	11	19	27	36	44	52	60	68	76	84	92
0.25	11	19	27	35	43	51	59	67	76	84	92
0.30	11	19	27	35	43	51	59	67	75	83	91
0.35	10	18	27	35	43	51	59	67	75	83	91
0.40	10	18	26	34	42	50	58	66	75	83	91
0.45	10	18	26	34	42	50	58	66	74	82	90
0.50	2810	2818	2826	2834	2842	2850	2858	2866	2874	2882	2890
0.55	09	17	25	33	41	50	58	66	74	82	90
0.60	09	17	25	33	41	49	57	65	73	81	89
0.65	09	17	25	33	41	49	57	65	73	81	89
0.70	08	16	24	32	41	49	57	65	73	81	89
0.75	08	16	24	32	40	48	56	64	72	80	88
0.80	08	16	24	32	40	48	56	64	72	80	88
0.85	07	15	24	32	40	48	56	64	72	80	88
0.90	07	15	23	31	39	47	55	63	71	80	88
0.95	07	15	23	31	39	47	55	63	71	79	87
1.00	2807	2815	2823	2831	2839	2847	2855	2863	2871	2879	2887
1.05	06	14	22	30	38	46	54	62	70	78	86
1.10	06	14	22	30	38	46	54	62	70	78	86
1.15	05	13	22	30	38	46	54	62	70	78	86
1.20	05	13	21	29	37	45	53	61	69	77	85
1.25	05	13	21	29	37	45	53	61	69	77	85
1.30	04	12	20	28	36	45	53	61	69	77	85
1.35	04	12	20	28	36	44	52	60	68	76	84
1.40	04	12	20	28	36	44	52	60	68	76	84
1.45	03	11	19	27	35	43	51	59	67	75	83
1.50	2803	2811	2819	2827	2835	2843	2851	2859	2867	2875	2883
1.55	03	11	19	27	35	43	51	59	67	75	83
1.60	02	10	18	26	34	42	50	58	66	74	82
1.65	02	10	18	26	34	42	50	58	66	74	82
1.70	01	09	17	26	34	42	50	58	66	74	82
1.75	01	09	17	25	33	41	49	57	65	73	81
1.80	01	09	17	25	33	41	49	57	65	73	81
1.85	00	08	16	24	32	40	48	56	64	72	80
1.90	00	08	16	24	32	40	48	56	64	72	80
1.95	00	08	16	24	32	40	48	56	64	72	80
2.00	2799	2807	2815	2823	2831	2839	2847	2855	2863	2871	2879
2.05	99	07	15	23	31	39	47	55	63	71	79
2.10	98	06	14	22	30	38	46	54	62	70	78
2.15	98	06	14	22	30	38	46	54	62	70	78
2.20	98	06	14	22	30	38	46	54	62	70	78
2.25	97	05	13	21	29	37	45	53	61	69	77
2.30	97	05	13	21	29	37	45	53	61	69	77
2.35	96	04	12	20	28	36	44	52	60	68	76
2.40	96	04	12	20	28	36	44	52	60	68	76
2.45	95	03	11	19	27	35	43	51	59	67	75
2.50	2795	2803	2811	2819	2827	2835	2843	2851	2859	2867	2875
2.55	94	02	10	18	26	34	42	50	58	66	74
2.60	94	02	10	18	26	34	42	50	58	66	74
2.65	94	02	10	18	26	34	41	49	57	65	73
2.70	93	01	09	17	25	33	41	49	57	65	73
2.75	93	01	09	17	25	33	41	49	57	65	73
2.80	92	00	08	16	24	32	40	48	56	64	72
2.85	92	00	08	16	24	32	40	48	56	64	72
2.90	91	2799	07	15	23	31	39	47	55	63	71
2.95	91	99	07	15	23	31	39	47	55	63	71
3.00	2791	2799	2807	2815	2823	2830	2838	2846	2854	2862	2870
3.05	90	98	06	14	22	30	38	46	54	62	70
3.10	90	98	06	14	22	29	37	45	53	61	69
3.15	89	97	05	13	21	29	37	45	53	61	69
3.20	89	97	05	13	21	28	36	44	52	60	68
3.25	88	96	04	12	20	28	36	44	52	60	68
3.30	88	96	04	12	20	27	35	43	51	59	67
3.35	87	95	03	11	19	27	35	43	51	59	67
3.40	87	95	03	11	19	26	34	42	50	58	66
3.45	86	94	02	10	18	26	34	42	50	58	66

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°											
3.50	2786	2794	2802	2810	2818	2825	2833	2841	2849	2857	2865
3.55	85	93	01	09	17	25	33	41	49	57	65
3.60	85	93	01	09	17	24	32	40	48	56	64
3.65	84	92	00	08	16	24	32	40	48	56	64
3.70	84	92	00	08	16	23	31	39	47	55	63
3.75	83	91	2799	07	15	23	31	39	47	55	63
3.80	83	91	99	07	15	22	30	38	46	54	62
3.85	82	90	98	06	14	22	30	38	46	54	62
3.90	82	90	98	06	14	21	29	37	45	53	61
3.95	81	89	97	05	13	21	29	37	45	53	61
4.00	2781	2789	2797	2805	2813	2820	2828	2836	2844	2852	2860
4.05	80	88	96	04	12	20	28	36	44	52	60
4.10	80	88	96	03	11	19	27	35	43	51	59
4.15	79	87	95	03	11	19	27	35	43	50	58
4.20	79	86	94	02	10	18	26	34	42	50	58
4.25	78	86	94	02	10	18	26	33	41	49	57
4.30	77	85	93	01	09	17	25	33	41	49	57
4.35	77	85	93	01	09	16	24	32	40	48	56
4.40	76	84	92	00	08	16	24	32	40	48	56
4.45	76	84	92	00	07	15	23	31	39	47	55
4.50	2775	2783	2791	2799	2807	2815	2823	2831	2839	2847	2855
4.55	75	82	90	98	06	14	22	30	38	46	54
4.60	74	82	90	98	06	14	22	30	38	45	53
4.65	73	81	89	97	05	13	21	29	37	45	53
4.70	73	81	89	97	05	13	21	28	36	44	52
4.75	72	80	88	96	04	12	20	28	36	44	52
4.80	72	80	88	96	04	11	19	27	35	43	51
4.85	71	79	87	95	03	11	19	27	35	43	50
4.90	71	79	87	94	02	10	18	26	34	42	50
4.95	70	78	86	94	02	10	18	26	33	41	49
5.00	2770	2778	2785	2793	2801	2809	2817	2825	2833	2841	2849
5.05	69	77	85	93	01	09	16	24	32	40	48
5.10	68	76	84	92	00	08	16	24	32	40	48
5.15	68	76	84	91	2799	07	15	23	31	39	47
5.20	67	75	83	91	99	07	15	23	30	38	46
5.25	66	74	82	90	98	06	14	22	30	38	46
5.30	66	74	82	90	98	05	13	21	29	37	45
5.35	65	73	81	89	97	05	13	21	29	36	44
5.40	65	73	81	88	96	04	12	20	28	36	44
5.45	64	72	80	88	96	04	12	19	27	35	43
5.50	2763	2771	2779	2787	2795	2803	2811	2819	2827	2835	2843
5.55	63	71	79	87	94	02	10	18	26	34	42
5.60	62	70	78	86	94	02	10	18	25	33	41
5.65	62	69	77	85	93	01	09	17	25	33	41
5.70	61	69	77	85	93	01	08	16	24	32	40
5.75	60	68	76	84	92	00	08	16	24	31	39
5.80	60	68	76	83	91	2799	07	15	23	31	39
5.85	59	67	75	83	91	99	07	14	22	30	38
5.90	59	66	74	82	90	98	06	14	22	30	38
5.95	58	66	74	82	89	97	05	13	21	29	37
6.00	2757	2765	2773	2781	2789	2797	2805	2813	2820	2828	2836
6.05	57	64	72	80	88	96	04	12	20	28	36
6.10	56	64	72	80	88	95	03	11	19	27	35
6.15	55	63	71	79	87	95	03	10	18	26	34
6.20	55	63	70	78	86	94	02	10	18	26	34
6.25	54	62	70	78	85	93	01	09	17	25	33
6.30	53	61	69	77	85	93	01	08	16	24	32
6.35	53	60	68	76	84	92	00	08	16	24	31
6.40	52	60	68	76	83	91	2799	07	15	23	31
6.45	51	59	67	74	83	91	99	06	14	22	30
6.50	2751	2758	2766	2774	2782	2790	2798	2806	2814	2822	2829
6.55	50	58	66	74	81	89	97	05	13	21	29
6.60	49	57	65	73	81	89	97	04	12	20	28
6.65	49	56	64	72	80	88	96	04	12	19	27
6.70	48	56	64	72	79	87	95	03	11	19	27
6.75	47	55	63	71	79	87	94	02	10	18	26
6.80	47	54	62	70	78	86	94	10	10	17	25
6.85	46	54	62	69	77	85	93	01	09	17	25
6.90	45	53	61	69	77	85	92	00	08	16	24
6.95	45	52	60	68	76	84	92	00	07	15	23

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°											
7.00	2744	2752	2760	2768	2775	2783	2791	2799	2807	2815	2823
7.05	43	51	59	67	75	82	90	98	06	14	22
7.10	42	50	58	66	74	82	90	98	05	13	21
7.15	42	50	57	65	73	81	89	97	05	12	20
7.20	41	49	57	65	72	80	88	96	04	12	20
7.25	40	48	56	64	72	80	87	95	03	11	19
7.30	40	47	55	63	71	79	87	95	02	10	18
7.35	39	47	54	62	70	78	86	94	02	10	17
7.40	38	46	54	62	70	77	85	93	01	09	17
7.45	37	45	53	61	69	77	84	92	00	08	16
7.50	2737	2744	2752	2760	2768	2776	2784	2792	2799	2807	2815
7.55	36	44	52	59	67	75	83	91	99	07	14
7.60	35	43	51	59	67	74	82	90	98	06	14
7.65	34	42	50	58	66	74	82	89	97	05	13
7.70	34	42	49	57	65	73	81	89	97	04	12
7.75	33	41	49	56	64	72	80	88	96	04	11
7.80	32	40	48	56	64	72	79	87	95	03	11
7.85	31	39	47	55	63	71	79	86	94	02	10
7.90	31	39	47	54	62	70	78	86	94	01	09
7.95	30	38	46	54	61	69	77	85	93	01	09
8.00	2729	2737	2745	2753	2761	2769	2776	2784	2792	2800	2808
8.05	29	36	44	52	60	68	76	83	91	2799	07
8.10	28	36	43	51	59	67	75	83	91	98	06
8.15	27	35	43	50	58	66	74	82	90	98	05
8.20	26	34	42	50	58	65	73	81	89	97	05
8.25	25	33	41	49	57	65	72	80	88	96	04
8.30	25	33	40	48	56	64	72	80	87	95	03
8.35	24	32	40	47	55	63	71	79	87	94	02
8.40	23	31	39	47	54	62	70	78	86	94	01
8.45	22	30	38	46	54	61	69	77	85	93	01
8.50	2722	2729	2737	2745	2753	2761	2769	2776	2784	2792	2800
8.55	21	29	36	44	52	60	68	76	83	91	2799
8.60	20	28	36	43	51	59	67	75	83	90	98
8.65	19	27	35	43	50	58	66	74	82	90	97
8.70	18	26	34	42	50	58	65	73	81	89	97
8.75	18	25	33	41	49	57	65	72	80	88	96
8.80	17	25	33	40	48	56	64	72	79	87	95
8.85	16	24	32	39	47	55	63	71	79	86	94
8.90	15	23	31	39	47	54	62	70	78	86	94
8.95	14	* 22	30	38	46	54	61	69	77	85	93
9.00	2714	2722	2729	2737	2745	2753	2761	2768	2776	2784	2792
9.05	13	21	29	36	44	52	60	68	75	83	91
9.10	12	20	28	36	43	51	59	67	75	82	90
9.15	11	19	27	35	42	50	58	66	74	82	89
9.20	10	18	26	34	42	49	57	65	73	81	89
9.25	10	17	25	33	41	49	56	64	72	80	88
9.30	09	17	24	32	40	48	56	63	71	79	87
9.35	08	16	24	31	39	47	55	63	70	78	86
9.40	07	15	23	31	38	46	54	62	70	77	85
9.45	06	14	22	30	37	45	53	61	69	76	84
9.50	2705	2713	2721	2729	2737	2744	2752	2760	2768	2776	2784
9.55	05	12	20	28	36	44	51	59	67	75	83
9.60	04	12	19	27	35	43	51	58	66	74	82
9.65	03	11	18	26	34	42	50	58	65	73	81
9.70	02	10	18	25	33	41	49	57	65	72	80
9.75	01	09	17	25	32	40	48	56	64	72	79
9.80	00	08	16	24	32	39	47	55	63	71	78
9.85	00	07	15	23	31	39	46	54	62	70	78
9.90	2699	07	14	22	30	38	46	53	61	69	77
9.95	98	06	13	21	29	37	45	52	60	68	76
10.00	2697	2705	2713	2720	2728	2736	2744	2752	2759	2767	2775
10.05	96	04	12	20	27	35	43	51	59	66	74
10.10	95	03	11	19	27	34	42	50	58	65	73
10.15	94	02	10	18	26	33	41	49	57	65	72
10.20	94	01	09	17	25	33	40	48	56	64	71
10.25	93	00	08	16	24	32	39	47	55	63	71
10.31	92	.00	07	15	23	31	39	46	54	62	70
10.35	91	2699	06	14	22	30	38	45	53	61	69
10.40	90	98	06	13	21	29	37	45	52	60	68
10.45	89	97	05	12	20	28	36	44	51	59	67

Table 1. For computing density, σ, of sea water for various values of salinity, S,
and of temperature, t--Continued

Tempera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°								°			
10.50	2688	2696	2704	2712	2719	2727	2735	2743	2751	2758	2766
10.55	87	95	03	11	18	26	34	42	50	57	·65
10.60	86	94	02	10	18	25	33	41	49	57	64
10.65	86	93	01	09	17	24	32	40	48	56	63
10.70	85	93	00	08	16	24	31	39	47	55	63
10.75	84	92	2699	07	15	23	30	38	46	54	62
10.80	83	91	99	06	14	22	30	37	45	53	61
10.85	82	90	98	05	13	21	29	36	44	52	60
10.90	81	89	97	05	12	20	28	36	43	51	59
10.95	80	88	96	04	11	19	27	35	42	50	58
11.00	2679	2687	2695	2703	2711	2718	2726	2734	2742	2749	2757
11.05	78	86	94	02	10	17	25	33	41	48	56
11.10	78	85	93	01	09	16	24	32	40	48	55
11.15	77	84	92	00	08	15	23	31	39	47	54
11.20	76	83	91	2699	07	15	22	30	38	46	53
11.25	75	82	90	98	06	14	21	29	37	45	52
11.30	74	82	89	97	05	13	20	28	36	44	52
11.35	73	81	88	96	04	12	19	27	35	43	51
11.40	72	80	87	95	03	11	19	26	34	42	50
11.45	71	79	86	94	02	10	18	25	33	41	49
11.50	2670	2678	2686	2693	2701	2709	2717	2724	2732	2740	2748
11.55	69	77	85	92	00	08	16	23	31	39	47
11.60	68	76	84	91	2699	07	15	23	30	38	46
11.65	67	75	83	90	98	06	14	22	29	37	45
11.70	66	74	82	90	97	05	13	21	28	36	44
11.75	65	73	81	89	96	04	12	20	27	35	43
11.80	64	72	80	88	96	03	11	19	27	34	42
11.85	63	71	79	87	95	02	10	18	26	33	41
11.90	63	70	78	86	94	01	09	17	25	32	40
11.95	62	69	77	85	93	00	08	16	24	31	39
12.00	2661	2668	2676	2684	2692	2700	2707	2715	2723	2731	2738
12.05	60	67	75	83	91	99	06	14	22	30	37
12.10	59	67	74	82	90	98	05	13	21	29	36
12.15	58	66	73	81	89	97	04	12	20	28	35
12.20	57	65	72	80	88	96	03	11	19	27	34
12.25	56	64	71	79	87	95	02	10	18	26	33
12.30	55	63	70	78	86	94	01	09	17	25	32
12.35	54	62	69	77	85	93	00	08	16	24	31
12.40	53	61	68	76	84	92	2699	07	15	23	30
12.45	52	60	67	75	83	91	98	06	14	22	29
12.50	2651	2659	2666	2674	2682	2690	2697	2705	2713	2721	2728
12.55	50	58	65	73	81	89	96	04	12	20	27
12.60	49	57	64	72	80	88	95	03	11	19	26
12.65	48	56	63	71	79	87	94	02	10	18	25
12.70	47	55	62	70	78	86	93	01	09	17	24
12.75	46	54	61	69	77	85	92	00	08	16	23
12.80	45	53	60	68	76	84	91	2699	07	15	22
12.85	44	52	59	67	75	83	90	98	06	14	21
12.90	43	51	59	66	74	82	89	97	05	13	20
12.95	42	50	58	65	73	81	88	96	04	12	19
13.00	2641	2649	2657	2664	2672	2680	2687	2695	2703	2711	2718
13.05	40	48	55	63	71	79	86	94	02	10	17
13.10	39	47	54	62	70	78	85	93	01	09	16
13.15	38	46	53	61	69	77	84	92	00	08	15
13.20	37	45	52	60	68	76	83	91	2699	07	14
13.25	36	44	51	59	67	75	82	90	98	05	13
13.30	35	43	50	58	66	74	81	89	97	04	12
13.35	34	42	49	57	65	72	80	88	96	03	11
13.40	33	41	48	56	64	71	79	87	95	02	10
13.45	32	40	47	55	63	70	78	86	94	01	09
13.50	2631	2639	2646	2654	2662	2669	2677	2685	2693	2700	2708
13.55	30	37	45	53	61	68	76	84	91	2699	07
13.60	29	36	44	52	60	67	75	83	91	98	06
13.65	28	35	43	51	59	66	74	82	89	97	05
13.70	27	34	42	50	58	65	73	81	88	96	04
13.75	26	33	41	49	56	64	72	80	87	95	03
13.80	25	32	40	48	55	63	71	79	86	94	02
13.85	24	31	39	47	54	62	70	78	85	93	01
13.90	23	30	38	46	53	61	69	77	84	92	00
13.95	21	29	37	45	52	60	68	76	83	91	2699

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Temperature, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°											
14.00	2620	2628	2636	2644	2651	2659	2667	2674	2682	2690	2698
14.05	19	27	35	43	50	58	66	73	81	89	97
14.10	18	26	34	41	49	57	65	72	80	88	95
14.15	17	25	33	40	48	56	63	71	79	87	94
14.20	16	24	32	39	47	55	62	70	78	86	93
14.25	15	23	30	38	46	54	61	69	77	84	92
14.30	14	22	29	37	45	53	60	68	76	83	91
14.35	13	21	28	35	44	51	59	67	75	82	90
14.40	12	20	27	35	43	50	58	66	74	81	89
14.45	11	18	26	34	42	49	57	65	72	80	88
14.50	2610	2617	2625	2633	2641	2648	2656	2664	2671	2679	2687
14.55	09	16	24	32	39	47	55	63	70	78	86
14.60	08	15	23	31	38	46	54	62	69	77	85
14.65	06	14	22	30	37	45	53	60	68	76	83
14.70	05	13	21	29	36	44	52	59	67	75	82
14.75	04	12	20	27	35	43	51	58	66	74	81
14.80	03	11	19	26	34	42	49	57	65	73	80
14.85	02	10	18	25	33	41	48	56	64	71	79
14.90	01	09	17	24	32	40	47	55	63	70	78
14.95	01	08	15	23	31	39	46	54	62	69	77
15.00	2599	2607	2614	2622	2630	2637	2645	2653	2661	2668	2676
15.05	98	06	13	21	29	36	44	52	59	67	75
15.10	97	04	12	20	28	35	43	51	58	66	74
15.15	96	03	11	19	26	34	42	49	57	65	73
15.20	95	02	10	18	25	33	41	48	56	64	71
15.25	93	01	09	16	24	32	39	47	55	63	70
15.30	92	00	08	15	23	31	38	46	54	61	69
15.35	91	2599	06	14	22	30	37	45	53	60	68
15.40	90	98	05	13	21	28	36	44	52	59	67
15.45	89	97	04	12	20	27	35	43	50	58	66
15.50	2588	2595	2603	2611	2619	2626	2634	2642	2649	2657	2665
15.55	87	94	02	10	17	25	33	40	48	56	64
15.60	86	93	01	09	16	24	32	39	47	55	62
15.65	84	92	00	07	15	23	30	38	46	53	61
15.70	83	91	2599	06	14	22	29	37	45	52	60
15.75	82	90	97	05	13	21	28	36	44	51	59
15.80	81	89	96	04	12	19	27	35	42	50	58
15.85	80	88	95	03	11	18	26	34	41	49	57
15.90	79	86	94	02	10	17	25	33	40	48	56
15.95	78	85	93	01	08	16	24	31	39	47	54
16.00	2577	2584	2592	2600	2607	2615	2623	2630	2638	2646	2653
16.05	75	83	91	2598	06	14	21	29	37	45	52
16.10	74	82	90	97	05	13	20	28	36	43	51
16.15	73	81	88	96	04	11	19	27	34	42	50
16.20	72	80	87	95	03	10	18	26	33	41	49
16.25	71	78	86	94	01	09	17	24	32	40	47
16.30	70	77	85	93	00	08	16	23	31	39	46
16.35	68	76	84	91	2599	07	14	22	30	37	45
16.40	67	75	83	90	98	06	13	21	29	36	44
16.45	66	74	81	89	97	04	12	20	27	35	43
16.50	2565	2573	2580	2588	2596	2603	2611	2619	2626	2634	2642
16.55	64	71	79	87	94	02	10	17	25	33	40
16.60	63	70	78	86	93	01	09	16	24	32	39
16.65	61	69	77	84	92	00	07	15	23	30	38
16.70	60	68	76	83	91	2599	06	14	22	29	37
16.75	59	67	74	82	90	97	05	13	20	28	36
16.80	58	66	73	81	89	96	04	12	19	27	35
16.85	57	64	72	80	87	95	03	10	18	26	33
16.90	56	63	71	79	86	94	02	09	17	25	32
16.95	54	62	70	77	85	93	00	08	16	23	31
17.00	2553	2561	2569	2576	2584	2592	2599	2607	2614	2622	2630
17.05	52	60	67	75	83	90	98	06	13	21	29
17.10	51	58	66	74	81	89	97	04	12	20	27
17.15	50	57	65	73	80	88	96	03	11	19	26
17.20	48	56	64	71	79	87	94	02	10	17	25
17.25	47	55	62	70	78	85	93	01	08	16	24
17.30	46	54	61	69	77	84	92	00	07	15	23
17.35	45	52	60	68	75	83	91	2598	06	14	21
17.40	44	51	59	67	74	82	89	97	05	12	20
17.45	42	50	58	65	73	81	88	96	04	11	19

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tempera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°											
17.50	2541	2549	2556	2564	2572	2579	2587	2595	2602	2610	2618
17.55	40	48	55	63	71	78	86	93	01	09	16
17.60	39	46	54	62	69	77	85	92	00	08	15
17.65	37	45	53	60	68	76	83	91	2599	06	14
17.70	36	44	52	59	67	75	82	90	97	05	13
17.75	35	43	50	58	66	73	81	89	96	04	12
17.80	34	42	49	57	64	72	80	87	95	03	10
17.85	33	40	48	56	· 63	71	78	86	94	01	09
17.90	31	39	47	54	62	70	77	85	93	00	08
17.95	30	38	46	53	61	69	76	84	91	2599	07
18.00	2529	2537	2544	2552	2560	2567	2575	2583	2590	2598	2605
18.05	28	35	43	51	58	66	74	81	89	97	04
18.10	27	34	42	49	57	65	72	80	88	95	03
18.15	25	33	41	48	56	64	71	79	86	94	02
18.20	24	32	39	47	55	62	70	78	85	93	00
18.25	23	30	38	46	53	61	69	76	84	92	2599
18.30	22	29	37	44	52	60	67	75	83	90	98
18.35	20	28	36	43	51	58	66	74	81	89	97
18.40	19	27	34	42	50	57	65	72	80	88	95
18.45	18	25	33	41	48	56	64	71	79	86	94
18.50	2516	2524	2532	2539	2547	2555	2562	2570	2578	2585	2593
18.55	15	23	30	38	46	53	61	69	76	84	92
18.60	14	22	29	37	45	52	60	67	75	83	90
18.65	13	20	28	36	43	51	58	66	74	81	89
18.70	11	19	27	34	42	50	57	65	73	80	88
18.75	10	18	25	33	41	48	56	64	71	79	87
18.80	09	17	24	32	40	47	55	62	70	78	85
18.85	08	15	23	31	38	46	53	61	69	76	84
18.90	06	14	22	29	37	45	52	60	67	75	83
18.95	05	13	20	28	36	43	51	59	66	74	81
19.00	2504	2512	2519	2527	2534	2542	2550	2557	2565	2573	2580
19.05	03	10	18	26	33	41	48	56	64	71	79
19.10	01	09	17	24	32	39	47	55	62	70	78
19.15	00	08	15	23	31	38	46	53	61	69	76
19.20	2499	06	14	22	29	37	45	52	60	67	75
19.25	98	05	13	20	28	36	43	51	58	66	74
19.30	96	04	11	19	27	34	42	50	57	65	72
19.35	95	03	10	18	25	33	41	48	56	64	71
19.40	94	01	09	16	24	32	39	47	55	62	70
19.45	92	00	08	15	23	30	38	46	53	61	68
19.50	2491	2499	2506	2514	2521	2529	2537	2544	2552	2560	2567
19.55	90	97	05	13	20	28	35	43	51	58	66
19.60	88	96	04	11	19	27	34	42	49	57	65
19.65	87	95	02	10	18	25	33	40	48	56	63
19.70	86	93	01	09	· 16	24	32	39	47	54	62
19.75	85	92	00	07	15	23	30	38	45	53	61
19.80	83	91	2498	06	14	21	29	37	44	52	59
19.85	82	90	97	05	12	20	28	35	43	51	58
19.90	81	88	96	03	11	19	26	34	42	49	57
19.95	79	87	95	02	10	17	25	33	40	48	56
20.00	2478	2486	2493	2501	2509	2516	2524	2531	2539	2547	2554
20.05	77	84	92	00	07	15	22	30	38	45	53
20.10	75	83	91	2498	06	13	21	29	36	44	51
20.15	74	82	89	97	04	12	20	27	35	43	50
20.20	73	80	88	96	03	11	18	26	34	41	49
20.25	71	79	87	94	02	09	17	25	32	40	47
20.30	70	78	85	93	00	08	16	23	31	38	46
20.35	69	76	84	92	2499	07	14	22	30	37	45
20.40	67	75	83	90	98	05	13	21	28	36	43
20.45	66	74	81	89	96	04	12	19	27	34	42
20.50	2465	2472	2480	2488	2495	2503	2510	2518	2526	2533	2541
20.55	63	71	79	86	94	01	09	17	24	32	39
20.60	62	70	77	85	92	00	08	15	23	30	38
20.65	61	68	76	83	91	2499	06	14	21	29	37
20.70	59	67	75	82	90	97	05	13	20	28	35
20.75	58	66	73	81	88	96	04	11	19	26	34
20.80	57	64	72	79	87	95	02	10	17	25	33
20.85	/ 55	63	71	78	86	93	01	09	16	24	31
20.90	54	62	69	77	84	92	00	07	15	22	30
20.95	53	60	68	75	83	91	2498	06	13	21	29

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°											
21.00	2451	2459	2467	2474	2482	2489	2497	2504	2512	2520	2527
21.05	50	58	65	73	80	88	96	03	11	18	26
21.10	49	56	64	71	79	87	94	02	09	17	25
21.15	47	55	62	70	78	85	93	00	08	16	23
21.20	46	53	61	69	76	84	91	2499	07	14	22
21.25	44	52	60	67	75	82	90	98	05	13	20
21.30	43	51	58	66	73	81	89	96	04	11	19
21.35	42	49	57	64	72	80	87	95	02	10	18
21.40	40	48	55	63	71	78	86	93	01	09	16
21.45	39	46	54	62	69	77	84	92	00	07	15
21.50	2438	2445	2453	2460	2468	2475	2483	2491	2498	2506	2513
21.55	36	44	51	59	67	74	82	89	97	04	12
21.60	35	42	50	58	65	73	80	88	95	03	11
21.65	33	41	49	56	64	71	79	86	94	02	09
21.70	32	40	47	55	62	70	78	85	93	00	08
21.75	31	38	46	53	61	69	76	84	91	2499	07
21.80	29	37	44	52	60	67	75	82	90	98	05
21.85	28	35	43	51	58	66	73	81	89	96	04
21.90	26	34	42	49	57	64	72	80	87	95	02
21.95	25	33	40	48	55	63	71	78	86	93	01
22.00	2424	2431	2439	2446	2454	2462	2469	2477	2484	2492	2500
22.05	22	30	37	45	53	60	68	75	83	91	2498
22.10	21	28	36	44	51	59	66	74	82	89	97
22.15	19	27	35	42	50	57	65	73	80	88	95
22.20	18	26	33	41	48	56	64	71	79	86	94
22.25	17	24	32	39	47	55	62	70	77	85	92
22.30	15	23	30	38	46	53	61	68	76	83	91
22.35	14	21	29	37	44	52	59	67	74	82	90
22.40	12	20	28	35	43	50	58	65	73	81	88
22.45	11	19	26	34	41	49	56	64	72	79	87
22.50	2410	2417	2425	2432	2440	2447	2455	2463	2470	2478	2485
22.55	08	16	23	31	38	46	54	61	69	76	84
22.60	07	14	22	29	37	45	52	60	67	75	82
22.65	05	13	20	28	36	43	51	58	66	73	81
22.70	04	11	19	27	34	42	49	57	64	72	80
22.75	02	10	18	25	33	40	48	56	63	71	78
22.80	01	09	16	24	31	39	46	54	62	69	77
22.85	00	07	15	22	30	37	45	53	60	68	75
22.90	2398	06	13	21	28	36	44	51	59	66	74
22.95	97	04	12	20	27	35	42	50	57	65	73
23.00	2395	2403	2410	2418	2426	2433	2441	2448	2456	2463	2471
23.05	94	01	09	17	24	32	39	47	54	62	70
23.10	92	00	08	15	23	30	38	45	53	61	68
23.15	91	2399	06	14	21	29	36	44	52	59	67
23.20	90	97	05	12	20	27	35	42	50	58	65
23.25	88	96	03	11	18	26	33	41	49	56	64
23.30	87	94	02	09	17	24	32	40	47	55	62
23.35	85	93	00	08	15	23	31	38	46	53	61
23.40	84	91	2399	06	14	22	29	37	44	52	59
23.45	82	90	97	05	12	20	28	35	43	50	58
23.50	2381	2388	2396	2403	2411	2419	2426	2434	2441	2449	2456
23.55	79	87	94	02	10	17	25	32	40	47	55
23.60	78	85	93	01	08	16	23	31	38	46	53
23.65	76	84	92	2399	07	14	22	29	37	44	52
23.70	75	82	90	98	05	13	20	28	35	43	51
23.75	73	81	89	96	04	11	19	26	34	42	49
23.80	72	80	87	95	02	10	17	25	32	40	48
23.85	71	78	86	93	01	08	16	23	31	39	46
23.90	69	77	84	92	2399	07	14	22	30	37	45
23.95	68	75	83	90	98	05	13	21	28	36	43
24.00	2366	2374	2381	2389	2396	2404	2412	2419	2427	2434	2442
24.05	65	72	80	87	95	02	10	18	25	33	40
24.10	63	71	78	86	93	01	09	16	24	31	39
24.15	62	69	77	84	92	2399	07	15	22	30	37
24.20	60	68	75	83	90	98	06	13	21	28	36
24.25	59	66	74	81	89	96	04	12	19	27	34
24.30	57	65	72	80	87	95	03	10	18	25	33
24.35	56	63	71	78	86	93	01	09	16	24	31
24.40	54	62	69	77	84	92	00	07	15	22	30
24.45	53	60	68	75	83	90	2398	05	13	21	28

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Continued

Tem-pera-ture, t	Salinity, S, in °/oo										
	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
°24.50	2351	2359	2366	2374	2381	2389	2396	2404	2412	2419	2427
24.55	50	57	65	72	80	87	95	03	10	18	25
24.60	48	56	63	71	78	86	93	01	09	16	24
24.65	47	54	62	69	77	84	92	00	07	15	22
24.70	45	53	60	68	75	83	90	2398	06	13	21
24.75	44	51	59	66	74	81	89	97	04	12	19
24.80	42	50	57	65	72	80	87	95	03	10	18
24.85	41	48	56	63	71	78	86	94	01	09	16
24.90	39	47	54	62	69	77	84	92	00	07	15
24.95	38	44	53	60	68	75	83	91	2398	06	13
25.00	2336	2344	2351	2359	2366	2374	2381	2389	2397	2404	2412
25.05	35	42	50	57	65	72	80	87	95	03	10
25.10	33	41	48	56	63	71	78	86	93	01	09
25.15	32	39	47	54	62	69	77	84	92	2399	07
25.20	30	38	45	53	60	68	75	83	90	98	05
25.25	28	36	44	51	59	66	74	81	89	96	04
25.30	27	35	42	50	57	65	72	80	87	95	02
25.35	25	33	41	48	56	63	71	78	86	93	01
25.40	24	31	39	47	54	62	69	77	84	92	2399
25.45	22	30	37	45	53	60	68	75	83	90	98
25.50	2321	2328	2336	2343	2351	2359	2366	2374	2381	2389	2396
25.55	19	27	34	42	49	57	65	72	80	87	95
25.60	18	25	33	40	48	55	63	71	78	86	93
25.65	16	24	31	39	46	54	61	69	77	84	92
25.70	15	22	30	37	45	52	60	67	75	83	90
25.75	13	21	28	35	43	51	58	66	73	81	88
25.80	12	19	27	34	42	49	57	64	72	79	87
25.85	10	18	25	33	40	48	55	63	70	78	85
25.90	09	16	24	31	39	46	54	61	69	76	84
25.95	07	15	22	30	37	45	52	60	67	75	82
26.00	2305	2313	2321	2328	2336	2343	2351	2358	2366	2373	2381
26.05	04	11	19	26	34	42	49	57	64	72	79
26.10	02	10	17	25	32	40	47	55	63	70	78
26.15	01	08	16	23	31	38	46	53	61	68	76
26.20	2299	07	14	22	29	37	44	52	59	67	74
26.25	98	05	13	20	28	35	43	50	58	65	73
26.30	96	04	11	19	26	34	41	49	56	64	71
26.35	94	02	09	17	25	32	40	47	55	62	70
26.40	93	00	08	15	23	30	38	46	53	61	68
26.45	91	2299	06	14	21	29	36	44	51	59	67
26.50	2290	2297	2305	2312	2320	2327	2335	2342	2350	2357	2365
26.55	88	96	03	11	18	26	33	41	48	56	63
26.60	87	94	02	09	17	24	32	39	47	54	62
26.65	85	92	00	08	15	23	30	38	45	53	60
26.70	83	91	2298	06	13	21	29	36	44	51	59
26.75	82	89	97	04	12	19	27	34	42	50	57
26.80	80	88	95	03	10	18	25	33	40	48	55
26.85	79	86	94	01	09	16	24	31	39	46	54
26.90	77	85	92	00	07	15	22	30	37	45	52
26.95	75	83	90	2298	06	13	21	28	36	43	51
27.00	2274	2281	2289	2296	2304	2312	2319	2327	2334	2342	2349
27.05	72	80	87	95	02	10	17	25	32	40	47
27.10	71	78	86	93	01	08	16	23	31	38	46
27.15	69	77	84	92	2299	07	14	22	29	37	44
27.20	67	75	82	90	98	05	13	20	28	35	42
27.25	66	73	81	88	96	03	11	18	26	34	41
27.30	64	72	79	87	94	02	09	17	24	32	39
27.35	63	70	78	85	93	00	08	15	23	30	38
27.40	61	68	76	84	91	2299	06	14	21	29	36
27.45	59	67	74	82	89	97	04	12	20	27	35
27.50	2258	2265	2273	2280	2288	2295	2303	2310	2318	2325	2333
27.55	56	64	71	79	86	94	01	09	16	24	31
27.60	54	62	70	77	85	92	00	07	15	22	30
27.65	53	60	68	75	83	90	2298	06	13	21	28
27.70	51	59	66	74	81	89	96	04	11	19	26
27.75	50	57	65	72	80	87	95	02	10	17	25
27.80	48	56	63	71	78	86	93	01	08	16	23
27.85	46	54	62	69	76	84	91	2299	07	14	22
27.90	45	52	60	67	75	82	90	97	05	12	20
27.95	43	51	58	66	73	81	88	96	03	11	18

Table 1. For computing density, σ, of sea water for various values of salinity, S, and of temperature, t--Concluded

Tempera-ture, t	Salinity, S, in $^o/oo$										
°	35.0	35.1	35.2	35.3	35.4	35.5	35.6	35.7	35.8	35.9	36.0
28.00	2242	2249	2257	2264	2272	2279	2287	2294	2302	2309	2317
28.05	40	47	55	62	70	77	85	93	00	08	15
28.10	38	46	53	61	68	76	83	91	2298	06	13
28.15	37	44	52	59	67	74	82	89	97	04	12
28.20	35	42	50	57	65	73	80	88	95	03	10
28.25	33	41	48	56	63	71	78	86	93	01	08
28.30	32	39	47	54	62	69	77	84	92	2299	07
28.35	30	38	45	53	60	68	75	83	90	98	05
28.40	28	36	43	51	58	66	73	81	88	96	03
28.45	27	34	42	49	57	64	72	79	87	94	02
28.50	2225	2233	2240	2248	2255	2263	2270	2278	2285	2293	2300
28.55	23	31	38	46	53	61	68	76	83	91	2298
28.60	22	29	37	44	52	59	67	74	82	89	97
28.65	20	28	35	43	50	58	65	73	80	88	95
28.70	18	26	33	41	48	56	63	71	78	86	93
28.75	17	24	32	39	47	54	62	69	77	84	92
28.80	15	23	30	38	45	53	60	68	75	83	90
28.85	13	21	28	36	43	51	58	66	73	81	88
28.90	12	19	27	34	42	49	57	64	72	79	87
28.95	10	18	25	33	40	48	55	63	70	78	85
29.00	2208	2216	2223	2231	2238	2246	2253	2261	2269	2276	2284
29.05	07	14	22	29	37	44	52	59	67	74	82
29.10	05	13	20	28	35	43	50	58	65	73	80
29.15	03	11	18	26	33	41	48	56	63	71	78
29.20	02	09	17	24	32	39	47	54	62	69	77
29.25	00	08	15	23	30	38	45	53	60	68	75
29.30	2198	06	13	21	28	36	43	51	58	66	73
29.35	97	04	12	19	27	34	42	49	57	64	72
29.40	95	02	10	17	25	32	40	47	55	62	70
29.45	93	01	08	16	23	31	38	46	53	61	68
29.50	2192	2199	2207	2214	2222	2229	2237	2244	2252	2259	2267
29.55	90	97	05	12	20	27	35	42	50	57	65
29.60	88	96	03	11	18	26	33	41	48	56	63
29.65	86	94	01	09	16	24	31	39	46	54	61
29.70	85	92	2200	07	15	22	30	37	45	52	60
29.75	83	91	2198	06	13	21	28	36	43	51	58
29.80	81	89	96	04	11	19	26	34	41	49	56
29.85	80	87	95	02	10	17	25	32	40	47	55
29.90	78	86	93	00	08	15	23	30	38	45	53
29.95	76	84	91	2199	06	14	21	29	36	44	51
30.00	2175	2182	2190	2197	2205	2212	2220	2227	2235	2242	2250

Table 2. Corrections for depth and temperature and

(Tabular values are in

Depth dy-namic meters	Temperature, t, in degrees centigrade												
	-2	-1	0	1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	2	2	2	2	2	2	2	2	2	2	2	2	2
25	12	12	12	12	12	12	12	12	12	12	12	12	12
50	25	25	25	25	25	25	25	25	24	24	24	24	24
75	38	38	37	36	36	36	36	36	35	35	35	35	35
100	50	49	49	49	48	48	48	48	47	47	47	47	47
150	75	74	74	73	73	73	72	72	71	71	71	71	70
200	99	99	98	97	97	96	96	95	95	94	94	94	93
250	124	124	123	122	121	121	120	120	119	118	118	117	117
300	149	148	147	146	145	144	144	143	142	142	141	140	140
400	198	197	196	195	194	193	192	191	190	189	188	187	187
500	248	246	245	244	242	241	240	238	237	236	235	234	233
700	346	344	342	340	338	336	334	333	331	330	328	327	326
1000	493	490	487	484	482	479	476	474	472	470	468	466	464
1500	736	732	728	724	719	716	712	709	705	702	699	696	694
2000	977	971	965	960	954	949	945	940	936	931	927	924	920
2500	1214	1207	1200	1193	1187	1181	1175	1169	1164	1159	1154	1149	1145
3000	1451	1442	1434	1426	1419	1411	1404	1398	1391	1385	1379	1374	1369
3500	1684	1674	1665	1656	1647	1639	1631	1623	1616	1609	1602	1596	1590
4000	1915	1903	1893	1883	1873	1864	1855	1846	1838	1830	1823	1816	1809
4500	2144	2132	2120	2109	2098	2088	2078	2068	......	......	......	......	......
5000	2371	2358	2345	2333	2321	2309	2299	2288	......	......	......	......	......
5500	2596	2581	2567	2553	2541	......	......	......	......	......	......	......	......
6000	2819	2803	2788	2773	2760	......	......	......	......	......	......	......	......

for depth and salinity to obtain density of sea water

units of fifth decimal)

	Salinity, S, in o/oo														Depth dy-namic meters
15	20	25	30	30	31	32	33	34	35	36	37	38	39	40	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	5
11	11	11	11	0	0	0	0	0	0	0	0	0	0	0	25
23	23	23	23	0	0	0	0	0	0	0	0	0	0	0	50
35	34	34	34	0	0	0	0	0	0	0	0	0	0	0	75
46	45	45	45	1	1	0	0	0	0	0	0	0	- 1	- 1	100
69	68	67	66	1	1	1	0	0	0	0	0	- 1	- 1	- 1	150
92	90	89	87	2	1	1	1	0	0	0	- 1	- 1	- 1	- 2	200
115	113	111	...	2	2	1	1	0	0	0	- 1	- 1	- 1	- 2	250
137	136	134	...	2	2	1	1	0	0	0	- 1	- 1	- 2	- 2	300
183	181	179	...	3	3	2	1	1	0	-1	- 1	- 2	- 3	- 3	400
229	226	.....	...	4	3	3	2	1	0	-1	- 2	- 3	- 3	- 4	500
320	316	.....	...	6	5	3	2	1	0	-1	- 2	- 3	- 5	- 6	700
456	.....	.....	...	8	7	5	3	2	0	-2	- 3	- 5	- 7	- 8	1000
682	.....	.....	...	12	10	8	4	2	0	-2	- 4	- 8	-10	-12	1500
905	.....	.....	...	16	13	10	6	3	0	-3	- 6	-10	-13	-16	2000
1126	.....	.....	...	20	16	12	8	4	0	-4	- 8	-12	-16	-20	2500
1347	.....	.....	...	23	19	14	9	5	0	-5	- 9	-14	-19	-23	3000
1565	.....	.....	...	27	22	16	11	5	0	-5	-11	-16	-22	-27	3500
1780	.....	.....	...	30	24	18	12	6	0	-6	-12	-18	-24	-30	4000
......	.....	.....	...	34	27	20	14	7	0	-7	-14	-20	-27	-34	4500
......	.....	.....	...	37	30	22	15	8	0	-8	-15	-22	-30	-37	5000
......	.....	.....	...	...	...	...	16	8	0	-8	-16	.....	.....	.....	5500
......	.....	.....	...	...	...	...	17	9	0	-9	-17	.....	.....	.....	6000

Table 3. Corrections for protected deep-sea reversing thermometer because of differences between observed reading T', and reading, t, of auxiliary attached thermometer; total correction Δt is sum of tabular value (negative for negative values of T'- t) and index correction I*

Obs'd. temp. diff. (T'- t)	$(T' + v_0)$ in degrees centigrade									
	91	92	93	94	95	96	97	98	99	100
1	0.015	0.015	0.015	0.016	0.016	0.016	0.016	0.016	0.016	0.017
2	0.030	0.031	0.031	0.031	0.032	0.032	0.032	0.033	0.033	0.033
3	0.045	0.046	0.046	0.047	0.047	0.048	0.048	0.049	0.049	0.050
4	0.061	0.061	0.062	0.063	0.063	0.064	0.065	0.065	0.066	0.067
5	0.076	0.077	0.077	0.078	0.079	0.080	0.081	0.082	0.082	0.083
6	0.091	0.092	0.093	0.094	0.095	0.096	0.097	0.098	0.099	0.100
7	0.106	0.107	0.108	0.110	0.111	0.112	0.113	0.114	0.115	0.117
8	0.121	0.122	0.124	0.125	0.127	0.128	0.129	0.131	0.132	0.133
9	0.136	0.138	0.139	0.141	0.142	0.144	0.145	0.147	0.148	0.150
10	0.151	0.153	0.155	0.156	0.158	0.160	0.162	0.163	0.165	0.167
11	0.167	0.168	0.170	0.172	0.174	0.176	0.178	0.180	0.181	0.183
12	0.182	0.184	0.186	0.188	0.190	0.192	0.194	0.196	0.198	0.200
13	0.197	0.199	0.201	0.203	0.206	0.208	0.210	0.212	0.214	0.217
14	0.212	0.214	0.217	0.219	0.221	0.224	0.226	0.229	0.231	0.233
15	0.227	0.230	0.232	0.235	0.237	0.240	0.242	0.245	0.247	0.250
16	0.242	0.245	0.247	0.250	0.253	0.256	0.258	0.261	0.264	0.267
17	0.257	0.260	0.263	0.266	0.269	0.272	0.275	0.277	0.280	0.283
18	0.273	0.276	0.279	0.282	0.285	0.288	0.291	0.294	0.297	0.300
19	0.288	0.291	0.294	0.297	0.301	0.304	0.307	0.310	0.315	0.317
20	0.303	0.306	0.310	0.313	0.316	0.320	0.323	0.326	0.330	0.333
21	0.318	0.321	0.325	0.329	0.332	0.336	0.339	0.343	0.346	0.350
22	0.333	0.337	0.340	0.344	0.348	0.352	0.355	0.359	0.363	0.367
23	0.348	0.352	0.356	0.360	0.364	0.368	0.372	0.375	0.379	0.383
24	0.363	0.367	0.371	0.376	0.380	0.384	0.388	0.392	0.396	0.400
25	0.379	0.383	0.387	0.391	0.395	0.400	0.404	0.408	0.412	0.417
26	0.394	0.398	0.402	0.407	0.411	0.416	0.420	0.424	0.429	0.433
27	0.409	0.413	0.418	0.422	0.427	0.432	0.436	0.441	0.445	0.450
28	0.424	0.429	0.433	0.438	0.443	0.448	0.452	0.457	0.462	0.467
29	0.439	0.444	0.449	0.454	0.459	0.464	0.468	0.473	0.478	0.483
30	0.454	0.459	0.464	0.459	0.474	0.480	0.485	0.490	0.495	0.500
31	0.469	0.475	0.480	0.485	0.490	0.496	0.501	0.506	0.511	0.517
32	0.485	0.490	0.495	0.501	0.506	0.512	0.517	0.522	0.528	0.533
33	0.500	0.505	0.511	0.516	0.522	0.528	0.533	0.539	0.544	0.550
34	0.515	0.521	0.526	0.532	0.538	0.543	0.549	0.555	0.561	0.567
35	0.530	0.536	0.542	0.548	0.554	0.559	0.565	0.571	0.577	0.583
36	0.545	0.551	0.557	0.563	0.569	0.575	0.582	0.588	0.594	0.600
37	0.560	0.566	0.573	0.579	0.585	0.591	0.598	0.604	0.610	0.616
38	0.575	0.582	0.588	0.595	0.601	0.607	0.614	0.620	0.627	0.633
39	0.590	0.597	0.604	0.610	0.617	0.623	0.630	0.637	0.643	0.650
40	0.606	0.612	0.619	0.626	0.633	0.639	0.646	0.653	0.660	0.666
41	0.621	0.628	0.635	0.641	0.648	0.655	0.662	0.669	0.676	0.683
42	0.636	0.643	0.650	0.657	0.664	0.671	0.678	0.686	0.693	0.700
43	0.651	0.658	0.666	0.673	0.680	0.687	0.695	0.702	0.709	0.716
44	0.666	0.674	0.681	0.688	0.696	0.703	0.711	0.718	0.726	0.733
45	0.681	0.689	0.696	0.704	0.712	0.719	0.727	0.735	0.742	0.750
46	0.696	0.704	0.712	0.720	0.728	0.735	0.743	0.751	0.759	0.766
47	0.712	0.720	0.727	0.735	0.743	0.751	0.759	0.767	0.775	0.783
48	0.727	0.735	0.743	0.751	0.759	0.767	0.775	0.784	0.792	0.800
49	0.742	0.750	0.758	0.767	0.775	0.783	0.792	0.800	0.808	0.816
50	0.757	0.765	0.774	0.782	0.791	0.799	0.808	0.816	0.825	0.833
51	0.772	0.781	0.789	0.798	0.807	0.815	0.824	0.832	0.841	0.850
52	0.787	0.796	0.805	0.814	0.822	0.831	0.840	0.849	0.858	0.866
53	0.802	0.811	0.820	0.829	0.838	0.847	0.856	0.865	0.874	0.883
54	0.818	0.827	0.836	0.845	0.854	0.863	0.872	0.881	0.891	0.900
55	0.833	0.842	0.851	0.861	0.870	0.879	0.888	0.898	0.907	0.916
56	0.848	0.857	0.867	0.876	0.886	0.895	0.905	0.914	0.924	0.933
57	0.863	0.873	0.882	0.892	0.902	0.911	0.921	0.930	0.940	0.950
58	0.878	0.888	0.898	0.907	0.917	0.927	0.937	0.947	0.957	0.966
59	0.893	0.903	0.913	0.923	0.933	0.943	0.953	0.963	0.973	0.983
60	0.908	0.919	0.929	0.939	0.949	0.959	0.969	0.979	0.990	1.000

*Strictly speaking, Δt = tabular value + I + 0.000164 (T'+ v_0) I, but the term 0.00164 (T'+ v_0) I may be neglected for well-made thermometers for which I does not exceed 0°.1.

FIG. 1.—

GRAPH SHOWING CORRECTIONS FOR UNPROTECTED DEEP-SEA REVERSING THERMOMETERS

BASED ON $\Delta t = \dfrac{(T_w + v_0)(T - t)}{K}$ FOR JENA GLASS 59^{III} FOR WHICH K=6100

45
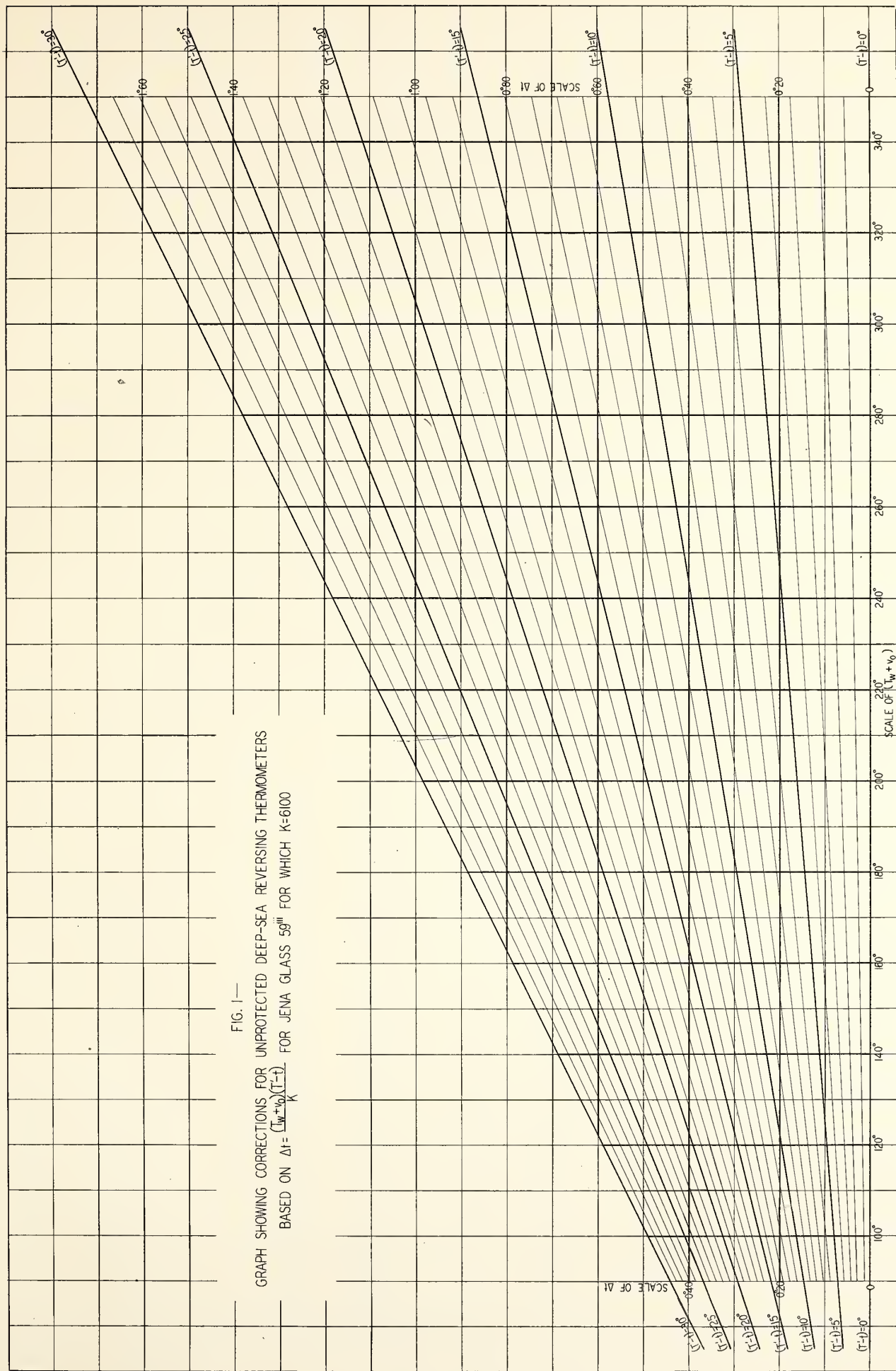
At a number of stations from station 7 to station 49 wire depths were obtained by the 4-mm wire. In all cases a water bottle provided with an unprotected and a protected thermometer was attached to the end of the wire and the depth was computed from the indications of the thermometers. The accuracy of this method has been discussed previously. No independent determinations of depth by means of the 4-mm wire were made and it is, therefore, unnecessary to enter on a discussion of the relation between wire length, wire angle, and depth at these stations.

At the greater number of the stations from 40 to 162 the depth was determined by means of sounding with piano wire. The wire angle was in many instances very great and it is, therefore, necessary to examine the relation between wire length, wire angle, and depth in these cases. In a number of cases a reversing frame, carrying two thermometers, one unprotected and one protected, was attached to the end of the wire. This frame was released by a propeller and according to experiments it had to be hauled up a distance of 25 meters before it was reversed. From the indications of the two thermometers the depth at which the frame was re-

versed can be computed with an accuracy of about ±0.5 per cent. Adding to this depth the distance of the frame from the lead at the end of the wire and the distance of 25 meters which the frame had to be hauled up before reversal, the depth at the station is obtained with the same accuracy. Omitting the observations at eight stations at which the frame evidently had reversed at a wrong level, thirty-four stations remain from which corresponding values of depth, wire length and wire angle are available. The data from these stations have been compiled in table 1 in which the cosine of the wire angle and the ratio between the observed depth and the wire length also are entered, the latter under the headline "depth factor." It is seen that the depth factor is usually smaller than the cosine of the wire angle at the surface, which means that the wire angle decreased when approaching the bottom.

In figure 1 the depth factor has been plotted against the wire angle and the single values are grouped around a smooth curve. The scattering of the values is small, considering that the depth factor for any given wire angle depends on the curvature of the wire which again is controlled by the change of current with depth, and by the

Table 1. Comparison between wire length, wire angle, and thermometer depth at stations where sounding with piano wire was undertaken

Station no.	Wire length, meters	Wire angle, degrees	Cosine of wire angle	Thermometer depth, meters	Depth factor	Adopted depth factor	Wire depth, meters	Thermometer depth minus wire depth, meters
52	2873	18	0.951	2851	0.992	0.978	2810	41
64	3902	17	0.956	3879	0.994	0.979	3820	59
65	3698	25	0.906	3626	0.981	0.968	3580	46
67	1100	12	0.978	1089	0.990	0.986	1085	4
82	3937	47	0.682	3631	0.922	0.928	3654	-23
83	4100	25	0.906	3982	0.971	0.968	3969	13
84	4187	18	0.951	4121	0.984	0.978	4095	26
85	3814	5	0.996	3770	0.988	0.994	3791	-21
86	2175	19	0.946	2132	0.980	0.977	2125	7
110	3067	10	0.985	3036	0.990	0.988	3030	6
117	5410	22	0.927	5296	0.979	0.972	5259	37
127	4310	41	0.755	4018	0.932	0.940	4051	-33
127	4273	50	0.643	4034	0.944	0.921	3935	99
128	4105	51	0.629	3785	0.922	0.919	3772	13
128	4194	52	0.616	3826	0.912	0.916	3842	-16
131	4586	30	0.866	4418	0.963	0.960	4403	15
132	4456	35	0.819	4251	0.954	0.951	4238	13
133	4652	33	0.839	4426	0.951	0.954	4438	-12
134	4676	12	0.978	4528	0.968	0.986	4611	-83
135	4882	10	0.985	4695	0.962	0.988	4823	-128
137	5506	45	0.707	5208	0.946	0.932	5132	75
138	6057	65	0.423	5382	0.889	0.884	5354	28
139	5429	35	0.819	5030	0.927	0.951	5163	-133
140	5222	55	0.574	4762	0.912	0.910	4752	10
141	6018	45	0.707	5667	0.942	0.932	5609	58
142	6051	32	0.848	5787	0.956	0.956	5787	0
146	5328	58	0.530	4756	0.893	0.902	4806	-50
149	5556	35	0.819	5320	0.958	0.951	5284	36
150	4687	20	0.940	4553	0.971	0.975	4570	-17
151	5094	20	0.940	4918	0.965	0.975	4967	-49
159	5721	25	0.906	5545	0.969	0.968	5538	7
160	2728	25	0.906	2614	0.958	0.968	2641	-27
161	4584	13	0.974	4484	0.978	0.985	4515	-31
162	5221	0	1.000	5124	0.981	1.000	5221	-97

weight at the end of the wire, which was not kept constant, and by the speed of lowering. The depth factor corresponding to any given wire angle can be read off from the curve in figure 1 and the wire depth obtained by multiplying the wire length with this factor.

In order to estimate the probable errors of the wire depths which have been determined by this method, such wire depths have been computed in the cases in which the depth was determined independently by thermometer and entered in table 1 together with the differences between the wire depths and the thermometer depths. These differences, which are represented graphically in figure 2, increase with increasing depth, which means that the error in the wire depth increases with depth. All points except three fall inside the two straight lines which have been drawn in the figure, representing a difference of 2.5 per cent of the depth. Of this difference 0.5 per cent can be regarded as owing to uncertainty in the thermometer depth and the maximum error of the wire depth is thus about 2 per cent of the depth. It is evident from the graph and from the values in the table that the error of the wire depth as a rule is considerably smaller, especially if the depth is small. The result must be regarded as very satisfactory, considering that wire angles greater than 40° frequently occurred.

Summarizing the preceding discussion it can be stated that when sounding with piano wire has been undertaken and the wire length and wire angle recorded, the wire depth can be found by multiplying the wire length by a factor which is read off from figure 1. The wire depth which has been computed by this method has a maximum error of 2 per cent.
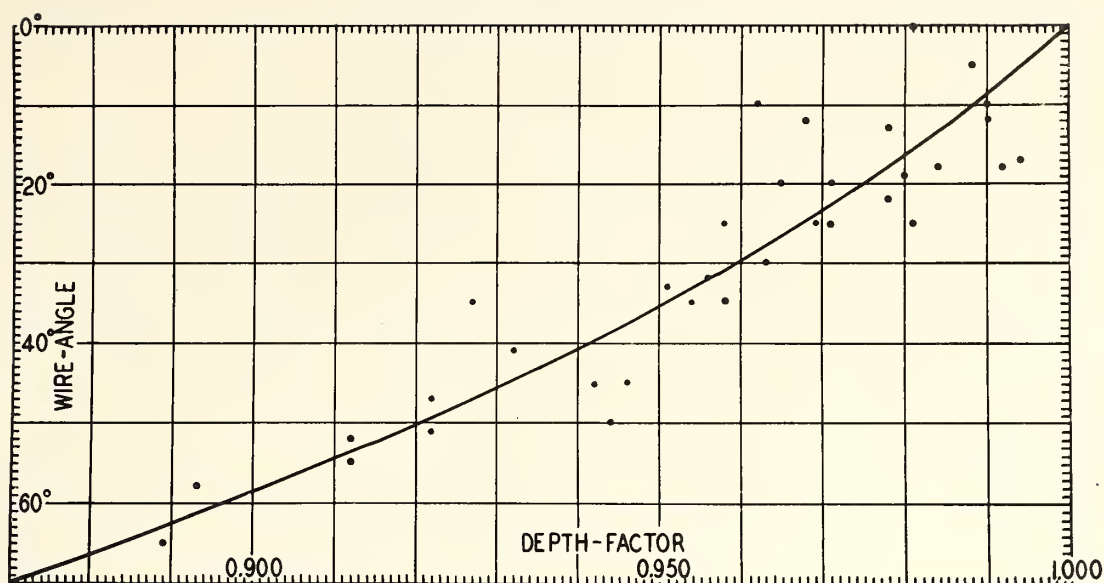
FIG.1- RELATION BETWEEN WIRE ANGLE AND FACTOR BY WHICH WIRE LENGTH MUST BE MULTIPLIED TO OBTAIN DEPTH WHEN SOUNDING WITH PIANO WIRE
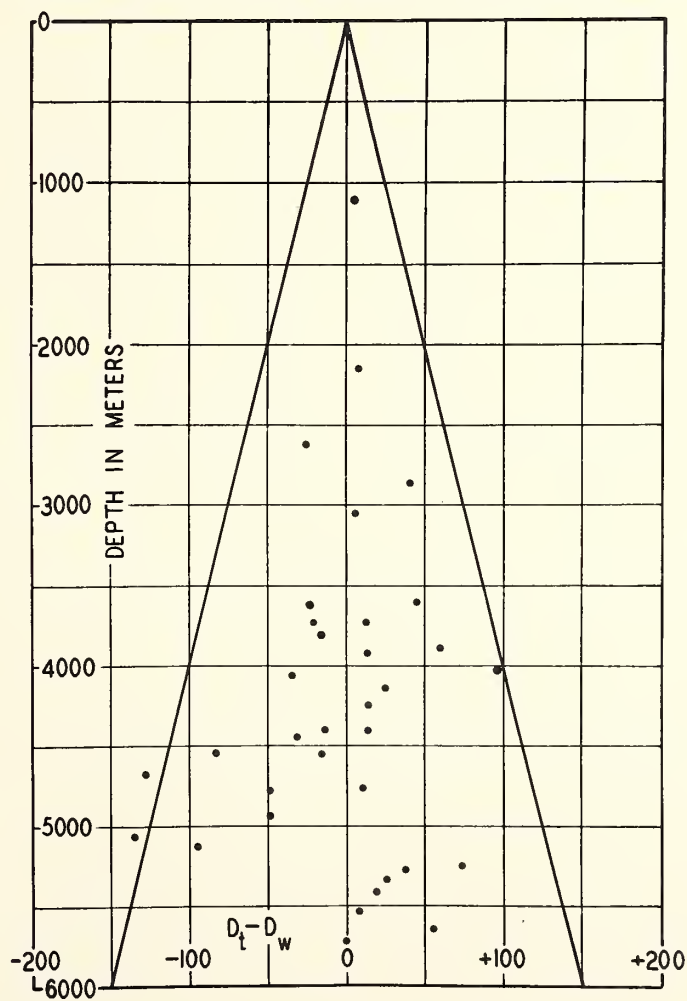
FIG. 2- THERMOMETER DEPTH (D_t) MINUS WIRE DEPTH (D_w) AS A FUNCTION OF DEPTH

During the summer of 1927 while the Carnegie was being overhauled prior to the beginning of her seventh cruise, sonic depth-finding equipment loaned by the United States Navy Department was installed. This equipment was of a type well suited for deep-sea sounding and consequently fitted the needs of the Carnegie. A Fessenden type of oscillator having a 30-inch steel diaphragm was located in the keel below the after part of the engine room. This oscillator, which was the source of sound of 540-cycle frequency, was actuated electromagnetically, being supplied with alternating current of 540-cycle frequency at 180 volts and direct current at 115 volts. A 5-kilowatt remote-controlled motor generator set for the alternating-current supply was located in the toolroom just off the engine room on the port side; the control panel was located in the engine room near the forward end. Six Navy hydrophones, any three of which could be used at one time, were located along the port garboard strake below the chartroom.

The depth finder proper was located in the control room (a deckhouse on the port side of the forward end of the quarter-deck). The depth finder acted as the clock for measuring the time required for the sound to travel from the surface to the bottom and return. It consisted of a tuning fork-controlled rotary converter which drove a large bakelite disc at constant speed. Riding on, and driven by this bakelite disc, was a smaller accurately machined brass disc mounted on a splined shaft carrying a series of commutators which made and broke the electrical circuit of a relay; this, in turn, operated the oscillator, thus sending out signals at periodic intervals. By means of a calibrated screw the radius at which the brass disc rode on the bakelite disc, and consequently the time interval between signals, was continuously variable between limits set by the dimensions of the bakelite disc. The outgoing signals and the returned echoes were audible in the telephone receivers, and in taking a sounding the position of the brass disc on the bakelite disc was adjusted until the outgoing signals occurred simultaneously with the returned echoes of the immediately preceding signals. Under this condition, the time required for a signal to travel to bottom and return was the same as the time interval between two successive signals. A dial operated by the calibrated screw indicated, in effect, the latter time interval.

A table, based on an arbitrarily selected sound velocity of 1450 meters per second, was made for converting dial readings into approximate depths, due consideration being given the horizontal distance between oscillator and hydrophones. As the velocity of sound in sea water is a variable depending chiefly on temperature, salinity, and pressure, the approximate depth was then multiplied by the suitable correction factor selected from a table applicable to the area in which the sounding was taken. To the value thus obtained, a further correction for draft was applied.

As originally installed, the outgoing signal was brought to the receivers from the secondary of an air-core transformer, the primary of which was in the alternating-current circuit of the oscillator. Thus there would be heard, first the electrically conducted impulse of the outgoing signal, then the outgoing signal as a direct sound wave picked up by the hydrophones, and finally the reflected sound wave as picked up by the hydrophones. As the first two arrived but a short time apart, it resulted in a blurred sound of considerable intensity, which had to be matched in time of arrival with a fainter sound of shorter duration. Later on the arrangement was changed and the air-core transformer eliminated, so that the outgoing signal was registered only as the direct sound wave picked up by the hydrophones. This resulted in a sharper outgoing signal in the receivers, and a consequently greater ease and accuracy in getting a balance. After this change in arrangement, a further constant correction of half the distance between oscillator and hydrophones was added.

The correction factors applicable to a certain locality were grouped into a table of ratios of the average velocity of sound down to the applicable depth, to the basic velocity of 1450 meters per second. These were based on the British Admiralty Hydrographic Department Publication No. 282 entitled "Tables of the velocity of sound in pure water and sea-water for use in echo-sounding and sound-ranging." The variation in pressure at a given depth, due to the variation in gravity with latitude, was considered to be small enough to be disregarded. The range in temperature normally encountered is from $-2°$ to $+30°$ C, whereas the salinity range is within 31.00 to 38.00 parts per thousand. Correction factors were computed for salinities of 31.00 and 38.00 parts per thousand and all even degrees of temperature from $-2°$ to $+30°$ C, using tables 2 and 3 of the British Admiralty publication cited above. From these factors a set of straight-line curves was drawn, one curve for each degree. Although the isothermal variation of velocity with salinity is not linear, it was sufficiently so for this purpose.

Curves based on the data in table 1 give the correction factor to the basic velocity at any salinity and temperature at atmospheric pressure. The amounts to be added to the values derived from table 1 because of pressure effect, as taken from table 4 of the British Admiralty publication, are shown in table 2.

A set of correction factors was prepared every two days from actually measured temperatures and salinities in the following manner. Vertical distribution curves of temperature and salinity were plotted, and from these curves were scaled the values at the nominal depths (in meters) of 0, 25, 50, 75, 100, 200, 300, 400, 500, 1000, 1500, 2000, etc. The temperature and salinity measurements usually extended to depths of from 2000 to 4000 meters. The vertical distribution curves were extrapolated to depths ordinarily about 500 meters greater than the deepest soundings obtained in the area in question. The extrapolations were made with the help of composite curves based on measurements made in areas where the deep water was homogeneous. These group extrapolations are discussed in the section on sounding velocity. From the velocity correction curves, values of corrections were obtained for the conditions of temperature and salinity prevailing at the nominal depths. To these were added the corrections, due to pressure, corresponding to the appropriate depth and temperature, and taken from table 2. The sum of these two corrections was entered in a column headed "velocity corrections" opposite the proper depth. The procedure for getting the

Table 1. Data used for graphs to determine correction factors to basic velocity at any salinity and temperature at atmospheric pressure

Temperature, °C	Salinity 31.00 per mille		Salinity 38.00 per mille	
	Velocity, m/sec	$\left[\dfrac{\text{Velocity}}{1450}\right]-1$	Velocity, m/sec	$\left[\dfrac{\text{Velocity}}{1450}\right]-1$
-2	1430.96	-.0131	1440.04	-.0069
-1	1435.68	-.0099	1444.72	-.0036
0	1440.30	-.0067	1449.30	-.0005
1	1444.92	-.0035	1453.88	+.0027
2	1449.34	-.0005	1458.26	+.0057
3	1453.76	+.0026	1462.64	+.0087
4	1458.08	+.0056	1466.92	+.0117
5	1462.20	+.0084	1471.00	+.0145
6	1466.34	+.0113	1475.08	+.0173
7	1470.38	+.0141	1479.06	+.0200
8	1474.32	+.0168	1482.94	+.0227
9	1478.16	+.0194	1486.72	+.0253
10	1481.90	+.0220	1490.40	+.0279
11	1485.56	+.0245	1493.94	+.0303
12	1489.12	+.0270	1497.38	+.0327
13	1492.68	+.0294	1500.82	+.0350
14	1496.04	+.0317	1504.06	+.0373
15	1499.30	+.0340	1507.20	+.0394
16	1502.52	+.0362	1510.38	+.0416
17	1505.54	+.0383	1513.36	+.0437
18	1508.56	+.0404	1516.34	+.0458
19	1511.48	+.0424	1519.22	+.0477
20	1514.30	+.0443	1522.00	+.0497
21	1517.04	+.0462	1524.68	+.0515
22	1519.78	+.0481	1527.36	+.0534
23	1522.42	+.0499	1529.94	+.0551
24	1524.96	+.0517	1532.42	+.0568
25	1527.50	+.0534	1534.90	+.0585
26	1529.92	+.0551	1537.28	+.0602
27	1532.24	+.0567	1539.56	+.0618
28	1534.56	+.0583	1541.84	+.0633
29	1536.88	+.0599	1544.12	+.0649
30	1539.00	+.0614	1546.20	+.0663

correction factors applicable to the various depths was from this point on a more or less obvious one of taking means. A specimen set of computations of correction factors is reproduced in table 3.

Criticism may be made of the arbitrary selection of the basic velocity of 1450 meters per second for the compilation of calibration tables. Consideration was given to the selection of some velocity which would have some significance other than merely being the base for a set of tables. For instance, such as the velocity of sound in water of 35.00 per mille salinity, 0° C temperature, and atmospheric pressure. So far as could be learned, however, practice had not crystallized to the point of selecting such a velocity which could be considered as standard, and as any velocity might be used equally as well as any other velocity, it was considered best for the purpose to select a figure which was approximately a round number, was somewhere near the true velocity, and would give corrections which would be additive in nearly all cases. It was for these reasons that 1450 meters per second was the velocity selected.

An estimate of the accuracy of each sounding was made and recorded at the time of the measurement. The method of arriving at these estimates may be of interest. The rotary converter and its controlling tuning fork were of 60-cycle frequency. As long as synchronism was maintained, the two had to maintain a phase relation which was constant within a quarter-cycle, and it is probable that the successful synchronizing range was about one-eighth of a cycle. This meant that relative to the tuning fork, the rotating parts were varying in phase by a maximum of 1/480 second or about 3 meters in distance. As the distance traveled was twice the depth, the uncertainty in depth due to this cause was about 1.5 meters. As there was no temperature control or compensation on the tuning fork, and as there was about 10° C range on either side of the mean, and as the tuning-fork rate had a temperature coefficient of about 0.007 per cent per degree centigrade, it was considered that the time intervals indicated were subject to an error of 0.1 per cent. Further, there was an uncertainty of the dial setting within which the outgoing and returning signals sounded as one to the operator. This uncertainty was converted into depth and if greater than 0.1 per cent and greater than 1.5 meters, it was recorded as the uncertainty of the measurement. If it was less than 0.1 per cent but greater than 1.5 meters, 0.1 per cent of the sounding was recorded as the uncertainty. And if the distance 1.5 meters was greater than both the uncertainty of setting and 0.1 per cent, then it was recorded as the uncertainty of measurement. It was thought that this was a reasonable procedure of estimating the accuracy of soundings. This is assuming, however, that the frequency of the tuning fork was accurately adjusted to 60 cycles per second, that the sounding velocity used was accurate, that the sounding distance was vertical, and that no gross errors were involved. The conditions of temperature and salinity at nearby oceanographic stations are on record, and if in the future it is found that the velocities used were inaccurate, corrections may be made. Very often echoes would be reflected from more than one surface. In such cases the first echo to return was selected as being from that surface which was most nearly vertically beneath the ship. Because of the comparatively gentle slopes of the ocean bottom, such a procedure is probably not greatly in error in soundings at sea, although it is recognized that in steep gradients, such as are encountered in certain approaches to land, the error may be considerable. Gross errors are possible when the returned echoes are matched with second or third succeeding signals instead of with the immediately succeeding signal, thus giving one-half, or one-third, the actual depth. Such errors are easily avoidable by sending single signals in order to determine the order of magnitude of the depth. As the single signal was usually used to determine the number of reflecting surfaces and the number of echoes, there was little possibility of gross errors entering the Carnegie results from this cause. Actually, the frequency of the tuning fork was not accurately adjusted to 60 cycles per second and corrections, which will be dealt with below, have been applied to the soundings taken with the sonic depth finder.

A program of sounding every four hours was attempted. During such times as the ship was becalmed or making little headway, soundings were taken about every ten miles. This program was, in general, followed but in areas of rapidly changing depth more frequent soundings were made. Other deviations from this schedule sometimes occurred to avoid interference with pilot-balloon ascensions, or radio schedules, and occasionally because of the press of other work. Short interruptions to the sounding program were sometimes caused by the necessity of making repairs to the depth finder or to the gasoline engine which drove the main generator. The

Table 2. Amounts to be added to correction factor because of pressure effect

Depth in meters	Temperature, °C		Amount	Depth in meters	Temperature, °C		Amount
	From	To			From	To	
25	-2	+25	.0003	500	-2	+5	.0063
50	-2	+25	.0006	1000	-2	+5	.0126
75	-2	+25	.0009	1500	-2	+5	.0188
100	-2	+25	.0012	2000	-2	+5	.0250
200	-2	+25	.0025	2500	-2	+3	.0313
300	-2	+25	.0037	3000	-2	+3	.0375
400	-2	+25	.0050	3500	-2	+3	.0437

Depth in meters	Temperature, °C				
	-1	0	+1	+2	+3
4000	.0499	.0499	.0499	.0499	.0498
4500	.0561	.0561	.0560	.0559	.0559
5000	.0623	.0621	.0621	.0621	.0619
5500	.0684	.0683	.0683	.0681	.0680
6000	.0745	.0744	.0743	.0742	.0741
6500	.0806	.0805	.0803	.0801	.0800
7000	.0866	.0865	.0863	.0861	.0859
7500	.0926	.0925	.0923	.0920	.0918
8000	.0986	.0984	.0981	.0979	.0977
8500	.1046	.1043	.1040	.1037	.1034
9000	.1104	.1101	.1099	.1095	.1092
9500	.1162	.1159	.1156	.1153	.1150

Table 3. Specimen determination of correction factors

Station 93; latitude 14° 41ʹ3 south, longitude 167° 40ʹ8 west; Sunday, March 31, 1929; Comp. F.M.S.

D	T_K	S	Vel. corr.	Mean corr. of layer			Sum of means	Corr. fact.
				25	100	500		
m	°	º/oo						
0	28.74	34.71	.0622		....	....	1.0624	1.0622
5	28.75	34.68	....	.0624		....	2.1248	....
25	28.75	34.76	.0625	.0624	.0624	....	3.1872	1.0624
50	28.50	34.78	.0624	.0624			4.2495	1.0624
75	28.05	35.40	.0624	.0623			2.1212[a]	1.0624
100	27.55	35.85	.0622		.0588	.0485	3.1715[a]	1.0624
200	22.65	36.04	.0555		.0503		4.2112[a]	1.0606
300	16.90	35.28	.0451		.0397		5.2425[a]	1.0572
400	11.70	34.75	.0343		.0313		....	1.0528
500	8.90	34.57	.0283			.0485	1.0485	1.0485
700	5.65	34.38	....			.0246	2.0731	....
1000	3.95	34.47	.0210			.0222	3.0953	1.0366
1500	2.70	34.52	.0235			.0258	4.1211	1.0318
2000	2.15	34.57	.0282			.0310	5.1521	1.0303
2500	1.90	34.63	.0337			.0366	6.1887	1.0304
3000	1.70	34.66	.0394			.0424	7.2311	1.0314
3500	1.60	34.67	.0453			.0481	8.2792	1.0330
4000	1.40	34.67	.0509			.0535	9.3327	1.0349
4500	1.10	34.67	.0561			.0592	10.3919	1.0370
5000	1.10	34.67	.0622			.0653	11.4572	1.0392
5500	1.10	34.67	.0684			.0714	12.5286	1.0416
6000	1.10	34.67	.0744					1.0440
6500								
7000								
7500								
8000								

[a]These values and all values below heavy line by extrapolation.

longest and most serious interruption was caused by the failure of the oscillator on November 3, 1928. It was not until Callao was reached that repairs to the oscillator could be made, since such repairs required dry-docking. Consequently, no accurate soundings were made between November 3, 1928 and February 6, 1929. Beginning November 14, 1928 rough soundings were made with an improvised shotgun. A steel breech just long enough to hold a 16-gage shotgun shell was screwed into one end of a length of brass pipe. The pipe acted as a holder and also as a guide for a heavy steel firing pin which was dropped into the upper and open end of the pipe, the shell end being held a foot or two below the surface. The hydrophones were used to pick up the echo and a stop wtach used to measure the elapsed time. Soundings were taken in this manner twice a day. These were only approximate because of the inaccuracy of the stop-watch measurement and because of the uncertainty of the velocity of a sound set up by an explosion. It was a case of half a loaf being better than none, however, and the device materially assisted in the routine occupation of oceanographic stations.

CORRECTIONS OF SONIC DEPTHS DETERMINED ON BOARD THE CARNEGIE ON ACCOUNT OF ERRORS IN THE TIMING

Depth was measured on board the <u>Carnegie</u> by three different methods, namely, by thermometers which were reversed at a short distance from the bottom, by wire soundings, and by sonic methods. The accuracy of soundings by thermometers or wire has been discussed and it has been shown that the depth obtained by thermometers can be regarded as reliable within ±0.5 per cent; the depths by wire soundings are reliable within ±2.0 per cent.

The accuracy of the depths determined by the sonic depth finder would be considerably greater than that of the other methods, supposing that no instrumental errors were present. Whether or not such errors occurred can be decided by examining the cases in which the depth was determined by thermometers or wire sounding close to a locality where the depth was measured by the sonic method. When making such an examination one must expect considerable variation in the results obtained by the different methods. This is partly because of the limited accuracy of the wire soundings, and partly because the sonic depth was not determined simultaneously with the other determination, for which reason irregularities of the bottom may give rise to discrepancies. The mean values obtained by the different methods, however, ought to agree if no systematic errors occur in the sonic depths.

When comparing the results by the different methods, it is to be noted that the timing of the sonic depth finder was readjusted February 19, 1929, and the comparison, therefore, must be made separately for the periods before and after this date. Table 1 gives the approximately simultaneous values of sonic depths and depths determined either by thermometers or by wire. The latter two are entered under the heading "true depth." The depths by thermometers have been entered, if available, because of the greater accuracy. The sonic depths entered in the table are derived from those sonic soundings which were made at the shortest distances from the locations at which the depths were determined by other methods. The last two columns of the table give the ratios between the true depths and the sonic depths, that is, the factor by which the sonic depth must be multiplied to obtain the true depth. The factors are arranged according to the character of the bottom. The bottom was regarded as being fairly regular when the difference between the two nearest sonic depths was less than 100 meters and the resulting factors are entered in the first of the last two columns. The bottom was regarded as irregular when the difference between the two nearest sonic depths exceeded 100 meters, and the resulting factors are entered in the last column.

It is seen that the sonic depths usually are greater than the depths by thermometers or wire. The bottom was extremely irregular or the wire depth was uncertain in a few outstanding cases, as is evident from the footnotes to the table. Omitting the nine cases indicated by these footnotes, fifty-nine approximately simultaneous values of sonic depths and thermometer or wire depths remain for comparison, twelve of which were obtained before, and forty-seven after, the readjustment of the timing February 19, 1929. The further discussion will be based on these fifty-nine cases only.

During the first period, using all twelve values, the mean sonic depth is 2871 meters, the mean true depth is 2683 meters, and the timing factor is 0.935. Using only the eight cases in which the depth was determined by means of thermometers, the mean sonic depth is 2327 meters, the mean true depth is 2197 meters, and the timing factor is 0.944.

The available data are much greater for the second period and a more detailed comparison between the sonic depths and the depths obtained by other methods can be made. The data of table 1 have been summarized in table 2, which gives the ratios between true depth and sonic depth for a number of different groups. The mean ratios were derived both from the mean depths and by forming the means of the single ratios. In the latter case the probable error of the mean value has been indicated.

From table 2 it is evident that the mean value of the ratio is practically independent of the grouping and also that the mean ratio, which is computed from the single ratios, agrees with the ratio of the mean depths. The latter feature shows that the ratio is nearly independent of depth. The mean errors in the last column show that the scattering of the single values of the ratio is smaller when the bottom is regular than when it is irregular, and also that the scattering is smaller when the true depth was determined by thermometers instead of by wire. Both these features should be expected. The irregular variations of the bottom and the greater error of the wire depths give rise to greater discrepancies.

From the preceding discussion it appears that the depths which were determined by means of the sonic depth finder during the period from February 19 to November 18, 1929 must be multiplied with a constant factor in order to give the true depth and the same evidently applies to the first period from May 13, 1928 to February 19, 1929. Considering that the most consistent results were obtained by comparison with depths which were determined by thermometers when the bottom was fairly regular, the following correction factors have been adopted for the soundings taken with the sonic depth finder: (1) May 13, 1928 to February 19, 1929, correction factor 0.944 and (2) February 19 to November 18, 1929, correction factor 0.964. The probable error of the latter factor is not greater than ±0.003, but the probable error of the former is perhaps ±0.009.

The instrumental error which makes application of these corrections to the sonic depths necessary must arise from an error of timing of the system. An error in the timing would lead to error in the sonic depth, which would be approximately proportional to the depth and therefore could be approximately eliminated by multiplication of the computed sonic depth with a constant factor. The fact that the correction factor was evidently changed when the timing was readjusted also indicates that the discrepancies arise from errors in timing. An error in timing should strictly be eliminated by correcting the time of echo before computing the sonic depth, but it can be shown that only an insignificant error is introduced by computing the sonic depth on the basis of the observed time of echo and correcting this computed depth by multiplication by a constant factor.

Table 1. Comparison of sonic depths with true depths as determined on the <u>Carnegie,</u> 1928-1929

Station no.	Sonic sounding no.	Sonic depth	True depth Thermometer ±0.5 per cent	Wire ±2 per cent	Ratio (true/sonic) Bottom regular	Bottom irregular
		m	m	m		
7	64	495	454	......	0.917	....
9	99	919	882	......	......	0.960
10	114	3210	3031	......	......	0.944
12	150	2849	2792	......	......	0.980
13	158	145	126	......	......	0.869
27	262	2831	......	2571	......	0.908
30	296	4988	4703	......	0.943	......
37	354	3500	3324	......	......	0.950
38	360	2512	2264	......	......	0.901
72	485	4819	......	4480	......	0.930
74	496	4565	......	4141[a]	0.907[a]	......
75	506	3912	......	3480	......	0.890
76	517	3387	......	2778[b]	......	0.820[b]
77	529	4275	......	4094	......	0.958
78[c]	536	3601	......	3337	0.927	......
79	547	3177	......	3064	......	0.964
79	547	3177	......	3116	......	0.981
80	559	3601	......	3515	0.976	......
81	572	3298	......	2953	......	0.895
82	585	3700	3631	......	......	0.981
83	596	4158	......	3966	0.954	......
84	609	4266	4121	......	0.966	......
85	622	3906	......	3791	0.971	......
86	658	2100	2132[d]	......	......	1.015[d]
87	672	4432	......	4315	0.974	......
94	759	4917	......	4760	0.968	......
96	779	5524	......	5269	0.954	......
97	789	5523	......	5253	......	0.951
108	921	4488	......	3573[e]	......	0.796[e]
109	932	5174	......	5252	1.015[f]	......
110	943	3172	3036	......	......	0.957
111	956	6106	......	6008	0.985	......
112	960	4445	3931[a]	......	......	0.884[a]
115	980	5636	......	5396	......	0.957
116	989	5902	......	5545	0.940	......
117	997	5525	5296	......	0.959	......
119	1015	5376	......	5198	......	0.967
127	1094	4296	4034	......	0.939	......
127	1094	4296	4018	......	0.935	......
128	1108	4118	3785	......	......	0.919
128	1108	4118	3826	......	......	0.929
131	1136	4597	4418	......	0.961	......
132	1151	4460	4251	......	0.953	......
133	1162	4545	4426	......	......	0.974
134	1172	4676	4528	......	......	0.968
135	1179	4829	4695	......	0.972	......
136	1187	4798	......	4713	0.982	......
137	1195	5339	5208	......	0.975	......
138	1206	5659	5382	......	......	0.951
139	1218	5262	5030	......	......	0.956
140	1227	4964	4762	......	......	0.959
141	1239	5847	5667	......	0.969	......
142	1249	5916	5787	......	......	0.978
145	1280	5728	......	5584	0.975	......
146	1289	5097	4756	......	......	0.933
147	1300	4893	......	4840	......	0.989·
148	1310	4993	......	4835	......	0.968
149	1321	5377	5320	......	0.989	......
150	1332	4284	4553[d]	......	......	1.063[d]
151	1344	5062	4918	......	......	0.972
153	1365	5226	......	5003	0.957	......
155	1385	5173	......	5304	1.025[g]	......
156	1396	5247	......	4953	......	0.944
157	1415	4134	......	4693[d]	......	1.135[d]
159	1453	5607	5545	......	......	0.989
160	1470	2699	2614	......	0.969	......
161	1481	2624	4484	......	0.970	......
162	1490	5248	4124	......	......	0.976

[a] Original record indicates wire length somewhat uncertain.   [b] Station probably on peak, sonic depths being much greater on either side.   [c] Timing sonic depth finder readjusted between stations 77 and 78.   [d] Station probably on slope, sonic depths being much greater on either side.   [e] Sonic depths show irregular bottom but not such that so large a discrepancy should be expected.   [f] On the slope of Fleming Deep.   [g] Wire depth uncertain on account of heavy current and resulting large wire angle.

The velocity of sound, determined from experiments in which the source of sound is an explosion, is greater than when the source used is a diaphragm vibrating with constant amplitude. Further, the difference in velocities is dependent on the distance involved and the violence of the explosion. This has been explained as being the result of a sound wave train of normal velocity superimposed on an explosive wave which suffers great attenuation. On this assumption the greater initial velocity is a transient phenomenon, after the disappearance of which the velocity becomes normal.

Following this line of reasoning, one should expect to find that the soundings taken on the Carnegie with the improvised shotgun would have to be corrected for this effect. On thirty-four occasions the time of echo was measured for more than the first echo. These times of echo were accordingly investigated and are given in table 3. In one case the time was measured from the explosion to the return of the fourth and fifth echoes, and in thirty-three cases times were measured for first and second echoes. Of the thirty-three cases there were two in which the time was recorded as being doubtful, and in another case an error of one second was apparently made in reading the stop watch for the time of the second echo. In the remaining thirty cases the time for the first echo was subtracted from the time for the first two echoes to obtain the time for the second echo. The differences between the times for the first and second echoes were then taken. In the case where the times for four and five echoes were measured, it was assumed that the times for the second and succeeding echoes were the same. From this, the time for the first echo was computed and compared with the time for the fifth echo. In these thirty-one cases the average difference between the times for the first and succeeding echoes was 0.113 seconds.

The echo times have, therefore, been corrected on the assumption that the times of all first echoes, as measured, were too small by this amount. This was done by adding 85 meters to the gross depths based on first echoes alone, 64 meters to the gross depths based on first and second echoes, and 42 meters to the gross depths based on second echoes alone. The shotgun soundings adjusted for this correction were then compared

with the wire depths and depths determined from pressure thermometers at the twenty oceanographic stations where such measurements were made. Of the twenty comparisons, the one made on Merriam Ridge (station 67) has been omitted because of the steep bottom slope in this vicinity. Because of the great distances between shotgun soundings, there is no way of telling when the bottom was regular and when irregular except in the previously mentioned case of Merriam Ridge. Therefore, as the shotgun soundings and accepted depths are only approximately simultaneous, a greater scatter must be expected than was found in the comparison of sonic depth finder soundings with accepted depths. A greater scatter must also be expected because a stop watch measurement of echo time is not as precise as an echo time measured by the sonic depth finder. Table 4 gives the approximately simultaneous depths as determined by wire and pressure thermometers and as given by the shotgun soundings corrected for greater intial velocity.

Comparison of the shotgun depths with corresponding wire and thermometer depths shows the shotgun soundings consistently greater (see fig. 1). The mean shotgun depth for the nineteen cases, excluding station 67, is 3621 meters, and the mean wire depth is 3471 meters, giving a ratio of means of 0.958+. The mean of the single ratios is 0.960- with a probable error of ±0.006.

In view of this a timing factor of 0.958 has been adopted and used for the correction of shotgun soundings after they were adjusted for the greater initial velocity resulting from the explosive character of the source of the sound. This makes the assumption that the stop watch had a large gaining rate. In May 1928 the stop watch was compared with a chronometer at the beginning and end of a two-hour run, and it checked so closely that it was considered permissible to use it as a time standard in the calibration of the depth finder timing. The depth finder was then adjusted until it was in agreement with the stop watch over a period of about fifteen minutes. The depth finder was similarly adjusted in February 1929 after it had been repaired and overhauled. The same stop watch was used in measuring the echo times for the shotgun soundings. In all three instances, that is, during the period from May 1928 to February 1929, the period from February 1929 to November 1929, and in the shotgun

Table 2. Summary of comparison between sonic depths and thermometer or wire depths at stations 78 to 162

Group	No. of cases	Mean depth in meters		Ratios of mean depths	Means of single ratios and their probable errors
		Sonic	True		
Depth by thermometer, bottom regular	12	4680	4510	0.964	0.963 ±0.0029
Depth by thermometer, bottom irregular	14	4796	4610	0.961	0.960 ±0.0038
Depth by wire, bottom regular	12	4825	4650	0.964	0.964 ±0.0035
Depth by wire, bottom irregular	9	4591	4401	0.959	0.957 ±0.0061
Bottom regular	24	4752	4580	0.964	0.963 ±0.0022
Bottom irregular	23	4716	4528	0.960	0.959 ±0.0032
Depth by thermometer	26	4742	4564	0.962	0.962 ±0.0024
Depth by wire	21	4724	4543	0.962	0.961 ±0.0032
All values	47	4734	4555	0.962	0.961 ±0.0019

Table 3. Showing difference in time required for first and succeeding echoes

Sound-ing no.	Time of		Mean time of			Sound-ing no.	Time of		Mean time of		
	First echo	First two echoes	First echo	Second echo	Differ-ence		First echo	First two echoes	First echo	Second echo	Differ-ence
363	3.2	9.6	3.2	6.4	+3.2[a]	441	4.7	9.6	.....	.....	....
364	5.2	10.4	.....	.....	....		4.6	9.6	4.65	4.95	+0.30
	5.3	10.1	5.25	5.00	−0.25	445	4.3	8.7	.....	.....	....
366	5.5	12.2	5.5	6.7	+1.2[b]		4.2	8.6	4.25	4.40	+0.15
369	4.5	9.5	.....	.....	....	446	4.7	9.7	4.7	5.0	+0.3
	4.5	9.8	4.50	5.15	+0.65[a]	447	5.0	10.2	5.0	5.2	+0.2
378	4.0	7.9	4.0	3.9	−0.1	450	4.8	10.1	.....	.....	....
379	4.0	7.5	.....	.....	....		4.9	10.2	4.85	5.30	+0.45
	3.8	7.7	3.90	3.70	−0.20	451	4.8	9.8	.....	.....	....
380	4.2	8.2	4.2	4.0	−0.2		4.8	9.9	4.80	5.05	+0.25
393	4.2	8.2	.....	.....	....	452	4.8	9.8	.....	.....	....
	3.9	8.2	.....	.....	....		4.7	9.7	4.75	5.00	+0.25
	4.4	8.6	4.17	4.17	±0.00	453	5.0	10.3	5.0	5.3	+0.3
395	4.5	9.0	.....	.....	....	460	1.8	3.5	.....	.....	....
	4.4	8.9	4.45	4.50	+0.05		1.5	3.5	1.65	1.85	+0.20
396	4.0	8.5	4.0	4.5	+0.5	463	5.5	11.0	5.5	5.5	±0.00
397	3.8	7.6	3.8	3.8	±0.00	464	5.5	11.1	5.5	5.6	+0.1
403	3.5	7.7	3.5	4.2	+0.7	466	5.8	11.4	.....	.....	....
414	4.2	8.7	.....	.....	....		5.8	11.6	5.80	5.70	−0.10
	4.2	8.3	4.20	4.30	+0.10	467	5.8	11.5	.....	.....	....
421	5.2	10.4	5.2	5.2	±0.00		5.5	11.2	5.65	5.70	+0.05
431	5.0	10.1	5.0	5.1	+0.1	470	5.	10.1	.....	.....	....
432	5.2	10.0	5.2	4.8	−0.4		5.6	10.1	5.05	5.05	±0.00
438	4.8	10.2	.....	.....	....	472	5.8	11.7	.....	.....	....
	5.2	10.2	5.00	5.20	+0.20		5.6[c]	11.8	5.70	6.05	+0.35
440	4.7	.....	.....	.....	....	475	3.1[c]	3.9[d]	0.70	0.80	+0.10
	....	9.5	4.7	4.8	+0.1						

Mean and probable error = +0.113 ±0.028

[a] Time questioned in original record. [b] Time of second echo apparently in error by one second.
[c] Time for first four echoes. [d] Time for first five echoes.

soundings, the ratios of true depth to indicated sonic depth have been of the same order of magnitude and less than unity. This can probably be reconciled with the comparison of stop watch and chronometer by considering that the stop watch had a faster rate during the first part of a run than during the latter part, such as the second hour, and that the initial fast rate was maintained during the first fifteen minutes. This seems to be be a reasonable assumption, and on such a basis the differences between the timing factors found for the shot-gun soundings and the first and second periods of the sonic depth finder are attributed to the changing rate of the stop watch. Viewed in this light it is to be noted that when these three timing factors are plotted against time they fall practically on a straight line. Such a plot is shown in figure 2, in which the date of the first adjustment of the depth finder is taken as May 28, 1928; the date of the shotgun ratio is taken as the mean date of the comparisons on which it is based, December 19, 1928; and the date of the second adjustment of the depth finder is taken as February 19, 1929.

These timing factors place the shotgun soundings and the sonic depth finder soundings all on a common basis, which is referred to the unprotected deep-sea reversing thermometers for a standard of depth.

Table 4. Comparison between shotgun soundings and soundings by wire or
unprotected thermometers

Station no.	Depths in meters			Ratios	
	Wire	Ther-mometer	Shotgun	Wire to shotgun	Thermometer to shotgun
43	3352	......	3716	0.902	....
46	2905	2840	2999	0.969	0.947
47	3080	......	2999	1.027	....
49	3028	......	3187	0.950	....
51	3063	2898	3180	0.963	0.911
52	2801	2851	2899	0.966	0.983
54	3063	......	3147	0.973	....
56	3135	......	3409	0.920	....
57	3139	......	3294	0.953	....
59	4116	......	4355	0.945	....
60	4007	......	4087	0.980	....
61	3299	......	3518	0.938	....
62	3610	......	3823	0.944	....
63	3393	......	3446	0.985	....
64	3820	3879	3880	0.985	1.000
65	3580	3626	3659	0.978	0.991
67	1085	1089	1278[a]	....	....
68 68	4146 } 4166 }	......	4309	0.964	....
69	3657	......	3845	0.951	....
70	4739	......	5054	0.938	....
			Average	0.960 ±0.006	

[a] Merriam Ridge

Note.--Omitting station 67, we have the following average ratios of depths: wire to
shotgun, 0.958; wire and thermometer where available, to shotgun, 0.957; thermometer
to shotgun, 0.969; wire to shotgun at stations where thermometer depths are available,
0.973.

FIG. 2—VARIATION OF TIMING FACTOR OF SONIC DEPTH FINDER FROM MAY 28, 1928 TO FEBRUARY 19, 1929

FIG. I—COMPARISON OF SHOTGUN DEPTHS WITH CORRESPONDING WIRE AND THERMOMETER DEPTHS

By sounding velocity is meant the average velocity of sound over a vertical path from the sea surface to the depth in question. As the sounding velocity is dependent on the actual velocity at intervals along the vertical path and as the actual velocity is a function of the temperature, salinity, and pressure, a knowledge of the vertical distribution of temperature and salinity is necessary before the sounding velocity at any point can be computed. The vertical distribution of temperature and salinity was determined from actual measurements at each oceanographic station (that is, about every other day) down to depths which were usually from 2000 to 4000 meters. The deep-water observations indicated that certain of the oceanographic stations had vertical temperature and salinity distributions sufficiently similar to be grouped together. Accordingly, all measured values below 2000 meters for a given group of stations were plotted on a single graph which was used for extrapolating the individual temperature and salinity curves for stations within that group. Scaled values of temperature and salinity for the nominal depth intervals down to 2500 meters are given for each oceanographic station in table 2 (see Oceanography I-B). Extrapolated values for depths below 2500 meters as determined by groups are shown in table 1. Wherever the vertical distribution curves based on actual measurements extend below 2500 meters, values scaled from these curves have been used instead of the values obtained from group extrapolation. The sounding velocities computed from the conditions found to exist at the oceanographic stations are given in table 5 (Oceanography I-B). In this table the values appearing below the heavy line are based on extrapolated temperatures or salinities. The sounding velocities given are probably significant to a few tenths of a meter per second as representing the conditions at the time measurements were made, but must not be relied on as representing the conditions at any other time.

There are seasonal variations in both temperature and salinity in the upper layers. Of these, the variations in temperature have the greater effect on sound velocity. In general, the temperate regions suffer the greatest annual variations in surface temperature, whereas the tropics and polar regions have smaller changes. Surface temperatures may vary as much as 10° C in the temperate regions and even more in the vicinity of the boundaries of pronounced streams such as the Japan Current and the Gulf Stream. Little is known regarding subsurface variations in temperature in the open ocean. It seems reasonable, however, to expect that annual variations occur to depths as great as those at which the rapid temperature decrease of the thermocline changes to the gradual temperature decrease at greater depths. Let us assume, then, that significant annual variations in temperature occur down to 500 meters and that the temperature at the surface may be 10° C different from the values measured on the Carnegie. Under such conditions the values of sounding velocity given in table 5 (Oceanography I-B) would be in error by about 0.2 per cent at a depth of 2500 meters and the error at 4000 meters would be about 2 meters per second.

Vertical sections showing the sounding velocity along the path of the Carnegie have been prepared from the computed values given in table 5 (Oceanography I-B).

These sections are approximately south-north and west-east, but the abscissas represent great circle distances between oceanographic stations. In order to show the variations, the vertical distances are shown on a scale which magnifies them 1000 times with respect to the horizontal scale. It is believed that sounding velocities shown in these sections, particularly in the Pacific, can be used to reduce future soundings in depths greater than 2500 meters not in the vicinity of pronounced streams with an error of less than one-fifth per cent in the sounding velocity. A horizontal section showing the sounding velocity at a level of 4000 meters (fig. 1) is given for the Pacific. An inspection of this indicates that the sounding velocities represented by the vertical sections can be applied to areas adjacent to the actual sections as follows: sections IV, VIII, X, XI, XII, and XIII apply 200 miles on each side; sections III, V, VI, XV, and XVI apply 100 miles on each side; sections VII, IX, and XIV apply 50 miles on each side.

In the British Admiralty Hydrographic Department Publication No. 282 entitled "Tables of the velocity of sound in pure water and sea-water for use in echo-sounding and sound-ranging" the oceans are divided into twenty-three areas within which echo soundings may be roughly reduced by means of appropriate tables of sounding velocity. The boundaries between these areas were intersected a number of times by the path of the Carnegie and the accompanying vertical sections consequently represent additional data on which to base the location of these boundaries. The boundary conditions were assumed to be the means of the sounding velocities given in the British Admiralty tables as applicable, at given depths, to the two adjacent areas. These boundary conditions were then located on the vertical sections, more attention being paid to the deeper layers than to the layers above the minimum. The boundary locations, as indicated by the Carnegie sections, are shown by broken lines superimposed on a chart giving the British Admiralty boundaries. This is shown in figures 2 and 3. The boundary between areas 17 and 6 is shifted somewhat to the south. Boundary 6 to 3 could not be very well located and has been omitted. Boundary 3 to 10 is shifted nearly 5° to the north. In the Pacific, boundary 18 to 20 seems to be south of the south end of Section III and east of the east end of Section X. Boundary 16 to 18, off the South American coast, is also shifted to the south. The eastern tip of boundary 16 to 13 is shifted westward through about 20° of longitude. Boundary 9 to 13 is apparently south and west of the Samoan Islands. The southern boundary of area 15 is shifted south and its northern boundary is shifted north. Boundary 13 to 16, north of Guam, is shifted south. Boundary 16 to 18, off the Japanese coast, is practically the same, and boundary 18 to 19 in this vicinity is the same. Boundary 19 to 21, however, is shifted considerably south, being south of the entire Section XVI. In view of this it seems probable that the northward bulge of boundary 18 to 19 is not so pronounced. The eastern end of boundary 18 to 19 is shifted but slightly to the south. Boundary 16 to 18 has an irregularity introduced northeast of the Hawaiian Islands. The boundary between areas 13 and 16, southeast of the Hawaiian Islands, could not be very well located on Section V. It seems probable that the values of

Table 1. Group extrapolation

Depth	3, 4, 5, 6, 10, and 11		12		14		2 and 15		16 to 19	
	Temp.	Salin.	Temp.	Salin.	Temp.	Salin.	Temp.	Salin.	Temp.	Salin.
m	°C	o/oo	°C	o/oo	°C	o/oo	°C	o/oo	°C	o/oo
3000	2.90	34.91	2.35	34.91	2.90	34.90	3.15	34.92	2.80	34.90
3500	2.80	34.90	2.30	34.90	2.55	34.89	2.80	34.91	2.65	34.89
4000	2.70	34.90	.....	....	2.25	34.89	2.50	34.90	2.60	34.88
4500	2.60	34.89	.....	....	2.20	34.88	2.40	34.88	2.50	34.87
5000	2.50	34.89	.....	....	.....	....	2.35	34.85	2.45	34.85
5500	2.45	34.88	.....	....	.....	....	2.25	34.83	2.40	34.83
6000	.....	....	.....	....	.....	....	2.20	34.82	2.35	34.82
6500	.....	....	.....	....	.....	....	.....	....	.....	....

Depth	58 to 62		63 to 67		47 and 68 to 79		80 to 92		93 to 94 and 160 to 162	
3000	1.75	34.69	1.75	34.66	1.80	34.68	1.70	34.66	1.70	34.66
3500	1.35	34.69	1.70	34.66	1.80	34.68	1.60	34.67	1.60	34.67
4000	1.10	34.69	1.70	34.67	1.80	34.68	1.45	34.67	1.40	34.67
4500	1.10	34.69	1.70	34.67	1.80	34.68	1.35	34.67	1.10	34.67
5000	1.10	34.69	1.70	34.67	1.80	34.68	1.30	34.67	1.10	34.67
5500	.....	....	.....	....	1.80	34.68	1.20	34.67	1.10	34.67
6000	.....	....	.....	....	1.80	34.68	1.15	34.67	1.10	34.67
6500	.....	....	.....	....	.....	....	1.15	34.67	.....	....
7000	.....	....	.....	....	.....	....	.....	....	.....	....
7500	.....	....	.....	....	.....	....	.....	....	.....	....
8000	.....	....	.....	....	.....	....	.....	....	.....	....
8500	.....	....	.....	....	.....	....	.....	....	.....	....
9000	.....	....	.....	....	.....	....	.....	....	.....	....

(Salinity values probably 0.03 o/oo too low; see page 72)

sounding velocity for either area 13 or 16 should be revised. The shifted boundaries are shown by broken lines of appreciable length, although only a single point is located at each crossing. To show these single points more definitely, lines have been drawn connecting the two oceanographic stations nearest each of these points of intersection.

As shown in one of the preceding sections (pp. 50-53), correction had to be applied to the sonic depths, owing to error in the timing, by multiplying the computed depths from various parts of the cruise by a constant factor. This has been done and the final values, together with their positions, are given in table 4 (Oceanography I-B).

It is believed that, except where otherwise noted in this table, the soundings are accurate within the following limits: soundings 0 to 360 inclusive, ± 1.0 per cent; soundings 361 to 476 inclusive, ± 1.5 per cent; soundings 477 to 534 inclusive, ± 1.0 per cent; and soundings 535 to 1496 inclusive, ± 0.5 per cent.

The sonic soundings listed in table 4 (Oceanography I-B) are nearly all shown graphically in twenty-eight bottom profiles, of which twelve have been plotted against latitude and sixteen have been plotted against longitude. The course followed by the Carnegie has been shown on each profile.

of temperature and salinity

| Station number | | | | | | | | | | | |
| 20 to 30 | | 31 to 34 | | 35 to 38 | | 39 to 45 | | 46 and 48 to 50 | | 51 to 57 | |
Temp.	Salin.	Temp.	Salin.	Temp.	Salin.	Temp.	Salin.	Temp.	Salin.	Temp.	Salin.
°C	o/oo	°C	o/oo	°C	o/oo	°C	o/oo	°C	o/oo	°C	o/oo
2.80	34.91	4.05	34.72	2.05	34.63	1.70	34.66	1.90	34.66	1.80	34.66
2.60	34.90	4.05	34.72	2.15	34.63	1.65	34.67	1.85	34.67	1.75	34.67
2.45	34.89	4.05	34.72	2.25	34.63	1.60	34.67	1.80	34.67	1.70	34.67
2.30	34.87	4.05	34.72	2.30	34.63	1.55	34.67	.....	....	.....	....
2.20	34.85	4.05	34.72	2.40	34.63	1.55	34.67	.....	....	.....	....
2.10	34.83	4.05	34.72	.....	....	.....	....	.....	....	.....	....
2.00	34.82	.....	....	.....	....	.....	....	.....	....	.....	....
1.90	34.81	.....	....	.....	....	.....	....	.....	....	.....	....

95 to 100		101 to 108		109 to 129		130 to 149		150		151 to 159	
1.70	34.64	1.65	34.64	1.60	34.64	1.60	34.64	1.65	34.65	1.75	34.65
1.65	34.65	1.60	34.65	1.55	34.64	1.50	34.64	1.55	34.66	1.55	34.66
1.60	34.65	1.60	34.65	1.55	34.64	1.55	34.65	1.40	34.65	1.40	34.65
1.60	34.65	1.55	34.65	1.55	34.64	1.55	34.65	1.40	34.64	1.40	34.64
1.55	34.66	1.55	34.66	1.55	34.64	1.50	34.65	1.50	34.64	1.50	34.64
1.55	34.66	1.55	34.66	1.55	34.64	1.60	34.65	1.35	34.64	1.35	34.64
1.60	34.66	1.60	34.66	1.60	34.64	1.65	34.65	1.20	34.64	1.20	34.64
1.70	34.67	1.70	34.67	1.70	34.64	1.70	34.65	.....	....	1.10	34.64
.....	....	1.75	34.67	1.75	34.64	.....	....	.....	....	.....	....
.....	....	1.85	34.67	1.85	34.64	.....	....	.....	....	.....	....
.....	....	1.90	34.67	1.90	34.64	.....	....	.....	....	.....	....
.....	....	2.00	34.67	2.00	34.64	.....	....	.....	....	.....	....
.....	....	.....	....	2.05	34.64	.....	....	.....	....	.....	....
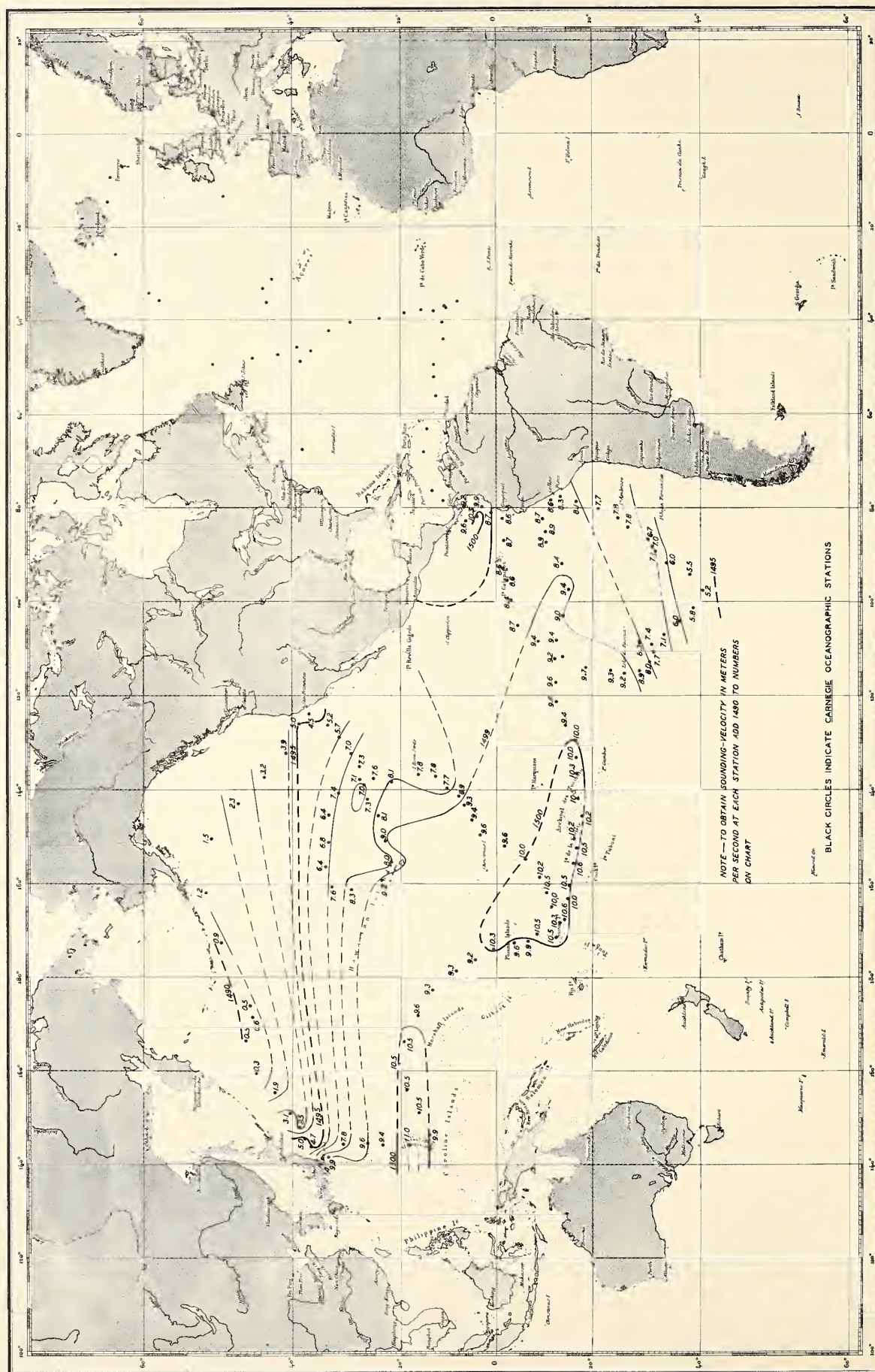
FIG I—HORIZONTAL DISTRIBUTION SOUNDING VELOCITY AT 4000 METERS, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1928-1929

NOTE—TO OBTAIN SOUNDING-VELOCITY IN METERS
PER SECOND AT EACH STATION ADD 1490 TO NUMBERS
ON CHART

BLACK CIRCLES INDICATE CARNEGIE OCEANOGRAPHIC STATIONS

FIG. 3 — AREAS SIMILAR SOUNDING VELOCITY CHARACTERISTICS, PACIFIC OCEAN,
FROM CARNEGIE RESULTS, 1928-1929

FIG. 2 — AREAS SIMILAR SOUNDING VELOCITY CHARACTERISTICS, ATLANTIC OCEAN,
FROM CARNEGIE RESULTS, 1928-1929

BASE-MAP FROM BRITISH
ADMIRALTY PUBLICATION
H. D. 282

The salinities were measured by the conductivity method using a Wenner salinity bridge (Wenner, Smith, and Soule, 1930). This instrument was of the type designed by Dr. Frank Wenner, of the Bureau of Standards, originally for the International Ice Patrol Service. It consists essentially of an alternating current Wheatstone's bridge, two adjacent arms of the bridge being formed by two similar electrolytic cells, the other two arms being made up of two fixed coils of manganin wire between which is a slide wire. The electrolytic cells are immersed in a stirred water bath which is thermostatically controlled at constant temperature. A substitution method is employed so that cell constants and absolute conductivities need not be known. Sea water, the salinity of which is unimportant within limits, is placed in one of the cells and sea water of known salinity is placed in the other cell. A small resistance in series with the first cell is then adjusted until the bridge is balanced when the slide-wire reading corresponds to the salinity of the known sample. This sample is then withdrawn and replaced by the unknown sample which is to be measured. The bridge is balanced this time by the adjustment of the slide wire, thus giving the conductivity of the unknown in terms of the known. The conductivities may be converted into salinities, but it is customary to calibrate the instrument by the measurement of a number of samples of known salinity so that the slide-wire reading may be converted directly into salinity without a knowledge of the relation between salinity and conductivity.

It can be assumed that the relation between salinity and conductivity is linear, but not proportional, over the range encountered in sea water. On this assumption the relation between slide-wire readings and salinity in an instrument of this sort can be expressed by an equation of the type

$$S = S' [1 + A(s - s') + B(s - s')^2 + C(s - s')^3 ....] \quad (1)$$

in which s is the slide-wire reading corresponding to any salinity S, and s' is the slide-wire reading corresponding to the salinity S', and A, B, C, ... are numerical constants depending on s', S', the relation between salinity and conductivity, and the constants of the bridge circuit. The numerical limits of the salinity range of such an instrument are fixed by the ratio of the resistance of one division of the slide wire to the resistance of the two bridge arms which include the slide wire, and by the arbitrary selection of the slide-wire reading s' which will correspond to the salinity S'. In the Carnegie instrument the slide wire had 1000 divisions, each of which had a resistance of 1/15,000 of the sum of the resistances of the two adjacent bridge arms which included the slide wire. Under these conditions, terms in equation (1) involving (s - s') to exponents greater than 3 are negligibly small and the third-degree term need only be considered when (s - s') is numerically large. When s' is selected near the middle of the slide wire, the second-degree equation can be used with negligible error.

In the case of this instrument a slide-wire reading s' of 699.5 was selected as corresponding to a salinity S' of 35.00 per mille, so that a second-degree equation can be used to express the calibration curve. If any

irregularities existed in the slide wire the calibration curve would have had departures from the curve of such an equation since the development of the equation assumes direct proportionality between slide-wire reading and slide-wire resistance.

Time did not permit of a test being made for uniformity of the slide wire before the departure of the Carnegie in May 1928. The preliminary calibration of the bridge was therefore made in the following manner. Standard water from the International Bureau at Copenhagen having a salinity of 34.99 per mille was placed in the test cells and the bridge was balanced with the slide wire set at a reading of 698.5. The slide-wire readings at balance were then determined for five other samples of known salinity furnished by the Scripps Institution of Oceanography, and titrated against Copenhagen standard water by H. R. Seiwell. A curve was then drawn through these six well-distributed points. From time to time, as the cruise progressed, some of the samples which were measured in the bridge were also titrated against standard water in a Knudsen burette by the silver nitrate method. Each of these samples furnished an additional point on the calibration curve. All such points ultimately obtained are shown in figure 1. The origin of these samples and the comparison values are given in table 1.

Because of the considerable range of room temperature encountered in a cruise such as that of the Carnegie, two regulating temperatures were provided for. In colder weather the water bath was regulated at a temperature of about 30° C and in the tropics a temperature of about 40° C was used. In the hope that the slope and curvature of the calibration curve at 40° C would be practically the same as for 30° C, the same arbitrary point, namely, salinity 34.99 per mille at slide-wire reading 698.5, was selected for each temperature. The points determined at a regulating temperature of 30° C are shown in figure 1 by circles and those determined at 40° C by crosses. The arbitrarily selected point is shown as a solid circle and cross. As there were no systematic differences between the points determined at the two temperatures, all points could be used in determining the calibration curve. This meant further that the exact temperature of regulation was unimportant as long as it did not change materially during a series of measurements.

Figure 1 includes all comparisons made on the Carnegie between bridge and titration methods. None was discarded. It includes all differences arising from both instrumental and observational error in both bridge and titration measurements, as well as any differences arising from variation in salt ratios in samples from different localities. As an individual bridge measurement is accurate to about 0.01 to 0.02 per mille salinity, and as an individual titration is subject to a similar error, it was expected that the points would scatter over from 0.02 to 0.04 per mille on each side of a smooth curve.

The second-degree equation whose curve fits the points shown in figure 1 is

$$S = 35 [1 + 295.7 \times 10^{-6} (s - 699.5)$$
$$+ 46. \times 10^{-9} (s - 699.5)^2] \quad (2)$$

The slide-wire readings of all the points shown in figure 1 were converted into salinities by this equation and their differences from the titration values plotted against

Table 1. Titration comparisons used in calibration of salinity bridge

Date		Sta-tion no.	Latitude	Longitude	Depth	Salinity by titration	Slide-wire reading	Nominal regulating temperature
Bridge	Titration							
1928	1928		° ′	° ′	m	°/oo		°C
July 15	....	8	63 30.1 N	14 40.7 W	0	35.23	720.6	30
15	....	8	63 30.1 N	14 40.7 W	300	35.26−	722.6	30
15	....	8	63 30.1 N	14 40.7 W	1000	35.09	708.5	30
Aug. 1	Aug. 7	11	58 12.1 N	35 51.4 W	581	34.93	692.2	30
5	7	12	51 39.8 N	49 31.7 W	435	34.82	685.6	30
16	....		Prepared sample			33.48	547.6	40
16			Prepared sample			36.20	809.5	40
Oct. 8	Oct. 9	33	13 37.2 N	76 22.5 W	661	34.74	674.8	40
26	27	35	6 32.5 N	80 04.1 W	27	33.50	554.7	40
Nov. 3	....	38	3 45.8 N	81 36.8 W	0	32.86	488.0	40
3	....	38	3 45.8 N	81 36.8 W	47	34.20	624.1	40
3	....	38	3 45.8 N	81 36.8 W	516	34.60	662.5	40
10	Nov. 10	41	1 36.6 S	86 58.2 W	6	34.19	621.0	30
10	10	41	1 36.6 S	86 58.2 W	23	34.53	653.6	30
10	10	41	1 36.6 S	86 58.2 W	323	34.83	682.3	30
13	14	42	1 32.2 S	93 09.7 W	0	34.70	672.6	30
13	14	42	1.32.2 S	93 09.7 W	578	34.59	661.7	30
13	14		Evaporimeter sample			34.41	642.0	30
19	19	45	4 35.1 S	105 03.4 W	238	34.87	689.1	30
19	19	45	4 35.1 S	105 03.4 W	310	34.86+	684.8	30
19	19	45	4 35.1 S	105 03.4 W	1176	34.60−	685.1	30
21	22	46	9 06.3 S	108 19.6 W	6	35.35	728.0	30
21	22	46	9 06.3 S	108 19.6 W	74	35.37	733.0	30
21	22	46	9 06.3 S	108 19.6 W	146	35.43	737.4	30
23	24	47	14 07.4 S	111 50.4 W	0	35.99−	787.3	30
23	24	47	14 07.4 S	111 50.4 W	5	35.99+	785.2	30
23	24	47	14 07.4 S	111 50.4 W	53	35.95	789.6	30
23	24	47	14 07.4 S	111 50.4 W	77	36.06−	795.3	30
23	24	47	14 07.4 S	111 50.4 W	95	36.15	805.6	30
23	24	47	14 07.4 S	111 50.4 W	205	35.70+	764.4	30
23	24	47	14 07.4 S	111 50.4 W	314	34.54−	657.8	30
23	24	47	14 07.4 S	111 50.4 W	425	34.62+	660.3	30
23	24	47	14 07.4 S	111 50.4 W	2044	34.63+	664.0	30
Dec. 5	Dec. 6	53	29 06.5 S	108 44.4 W	4	35.67	762.3	30
5	6	53	29 06.5 S	108 44.4 W	44	35.765	769.2	30
5	6	53	29 06.5 S	108 44.4 W	174	35.12+	713.6	30
5	6	53	29 06.5 S	108 44.4 W	309	34.75−	678.5	30
5	6	53	29 06.5 S	108 44.4 W	360	34.55−	655.2	30
5	6	53	29 06.5 S	108 44.4 W	543	34.32	635.2	30
5	6	53	29 06.5 S	108 44.4 W	794	34.28	631.0	30
5	6	53	29 06.5 S	108 44.4 W	1238	34.44−	649.1	30
5	6		Evaporimeter sample			35.70	766.0	30
26	26		Evaporimeter sample			37.68	948.6	30
26	26		Evaporimeter sample			37.23	906.0	30
26	26	60	40 23.9 S	97 32.7 W	0	33.93−	594.2	30
26	26	60	40 23.9 S	97 32.7 W	70	33.99	605.2	30
26	26	60	40 28.9 S	97 32.7 W	92	33.97	603.5	30
26	26	60	40 23.9 S	97 32.7 W	185	34.11	618.0	30
26	26	60	40 23.9 S	97 32.7 W	712	34.22	625.7	30
26	26	60	40 23.9 S	97 32.7 W	2600	34.63+	666.2	30
1929	1929							
Jan. 7	Jan. 8	66	27 04.4 S	84 01.1 W	6	34.70	670.2	30
7	8	66	27 04.4 S	84 01.1 W	48	34.79	680.0	30
7	8	66	27 04.4 S	84 01.1 W	96	34.94	694.9	30
7	8	66	27 04.4 S	84 01.1 W	193	34.50	653.8	30
7	8	66	27 04.4 S	84 01.1 W	293	34.41	645.4	30
7	8	66	27 04.4 S	84 01.1 W	391	34.45	647.2	30
7	8	66	27 04.4 S	84 01.1 W	751	34.37	639.9	30
7	8	66	27 04.4 S	84 01.1 W	1617	34.57	658.2	30
7	8	66	27 04.4 S	84.01.1 W	2606	34.63	666.8	30
7	8		Evaporimeter sample			37.59	939.8	30
Feb. 18	Feb. 18	77	14 20.0 S	103 12.5 W	0	36.04	794.5	30
18	18	77	14 20.0 S	103 12.5 W	69	36.02	793.1	30
18	18	77	14 20.0 S	103 12.5 W	92	35.97	791.0	30
18	18	77	14 20.0 S	103 12.5 W	182	35.43	736.8	30
18	18	77	14 20.0 S	103 12.5 W	2721	34.65	668.8	30
24	25	80	12 39.0 S	117 22.1 W	5	35.91	785.1	30
24	25	80	12 39.0 S	117 22.1 W	22	35.91	787.1	30
24	25	80	12 39.0 S	117 22.1 W	44	35.92	786.3	30
24	25	80	12 39.0 S	117 22.1 W	66	36.04	795.7	30
24	25	80	12 39.0 S	117 22.1 W	88	36.19	812.6	30
24	25	80	12 39.0 S	117 22.1 W	133	36.31−	820.6	30
24	25	80	12 39.0 S	117 22.1 W	180	35.82+	778.6	30
24	25	80	12 39.0 S	117 22.1 W	226	35.17	719.1	30
24	25	80	12 39.0 S	117 22.1 W	840			

Table 1. Titration comparisons used in calibration of salinity bridge--Continued

Date		Sta-tion no.	Latitude	Longitude	Depth	Salinity by titration	Slide-wire reading	Nominal regulating temperature
Bridge	Titration							
1929	1929		° ′	° ′	m	o/oo		°C
Feb. 24	Feb. 25	80	12 39.0 S	117 22.1 W	840	34.45	650.3	30
24	25		Evaporimeter sample			36.02	793.5	30
Mar. 2	Mar. 3		Evaporimeter sample			36.33	828.4	30
2	3	83	17 00.4 S	129 45.0 W	49	36.50	842.0	30
2	3	83	17 00.4 S	129 45.0 W	73	36.41	835.5	30
2	3	83	17 00.4 S	129 45.0 W	98	36.26	820.0	30
2	3	83	17 00.4 S	129.45.0 W	146	36.28	823.9	30
2	3	83	17 00.4 S	129 45.0 W	244	35.52	751.9	30
2	3	83	17 00.4 S	129 45.0 W	645	34.39	644.2	30
4	5	84	17 11.4 S	133 17.6 W	0	36.24	814.8	30
4	5	84	17 11.4 S	133 17.6 W	23	36.35	826.7	30
4	5	84	17 11.4 S	133 17.6 W	71	36.43+	835.2	30
4	5	84	17 11.4 S	133 17.6 W	190	36.17+	810.2	30
4	5	84	17 11.4 S	133 17.6 W	333	34.73	676.9	30
27	28	91	15 44.3 S	160 25.3 W	0	35.15	712.0	40
27	28	91	15 44.3 S	160 25.3 W	20	35.17	714.5	40
27	28	91	15 44.3 S	160 25.3 W	66	35.79	769.7	40
27	28	91	15 44.3 S	160 25.3 W	86	35.91	783.7	40
27	28	91	15 44.3 S	160 25.3 W	173	36.03	791.6	40
27	28	91	15 44.3 S	160 25.3 W	261	35.61	754.5	40
27	28	91	15 44.3 S	160 25.3 W	615	34.41	641.4	40
27	28	91	15 44.3 S	160 25.3 W	927	34.50	652.6	40
27	28	91	15 44.3 S	160 25.3 W	2269	34.62	660.8	40
27	28	91	15 44.3 S	160 25.3 W	2701	34.44	649.7	40
27	28	91	15 44.3 S	160 25;3 W	3863	34.67	666.8	40
May 9	May 10	102	16 24.9 N	171 59.3 E	84	34.99	699.8	40
9	10	102	16 24.9 N	171 59.3 E	126	35.08	707.0	40
9	10	102	16 24.9 N	171 59.3 E	170	35.23	721.7	40
9	10	102	16 24.9 N	171 59.3 E	255	34.94	696.9	40
9	10	102	16 24.9 N	171 59.3 E	338	34.33	636.9	40
9	10	102	16 24.9 N	171 59.3 E	423	34.20	624.8	40
9	10	102	16 24.9 N	171 59.3 E	987	34.49	651.0	40
9	10	102	16 24.9 N	171 59.3 E	2655	34.65	665.6	40
15	16	105	18 42.8 N	156 15.8 E	0	34.92	692.8	40
15	16	105	18 42.8 N	156 15.8 E	70	35.04	701.8	40
15	16	105	18 42.8 N	156 15.8 E	93	35.12	710.7	40
15	16	105	18 42.8 N	156 15.8 E	188	35.15	714.2	40
15	16	105	18 42.8 N	156 15.8 E	235	34.90	690.5	40
15	16	105	18 42.8 N	156 15.8 E	437	34.32	634.8	40
15	16	105	18 42.8 N	156 15.8 E	893	34.38	640.6	40
15	16	105	18 42.8 N	156 15.8 E	1693	34.57	660.4	40
27	28	108	18 26.1 N	144 01.2 E	23	34.99	696.9	40
27	28	108	18 26.1 N	144 01.2 E	281	34.79+	679.7	40
27	28	108	18 26.1.N	144 01.2 E	377	34.53	655.1	40
27	28	108	18 26.1 N	144 01.2 E	649	34.25	629.1	40
27	28	108	18 26.1 N	144 01.2 F	1412	34.55	657.8	40
27	28	108	18 26.1 N	144 01.2 E	2335	34.64-	663.9	40
June 3	June 4	111	31 00.1 N	144 16.2 E	71	34.70	668.2	40
3	4	111	31 00.1 N	144 16.2 E	187	34.74	673.6	40
3	4	111	31 00.1 N	144 16.2 E	377	34.44	644.3	40
3	4	111	31 00.1 N	144 16.2 E	471	34.15	617.2	40
3	4	111	31 00.1 N	144 16.2 E	483	34.14	618.0	40
3	4	111	31 00.1 N	144 16.2 E	559	34.08	611.5	40
3	4	111	31 00.1 N	144 16.2 E	565	33.97	601.4	40
July 1	July 2	116	38 40.9 N	147 41.2 E	0	33.99	606.3	30
1	2	116	38 40.9 N	147 41.2 E	22	33.96	603.5	30
1	2	116	38 40.9 N	147 41.2 E	43	33.77	581.7	30
1	2	116	38 40.9 N	147 41.2 E	65	34.03	609.0	30
1	2	116	38 40.9 N	147 41.2 E	444	34.10	613.0	30
1	2	116	38 40.9 N	147 41.2 E	535	34.18	621.4	30
1	2	116	38 40.9 N	147 41.2 E	668	34.24	628.4	30
1	2	116	38 40.9 N	147 41.2 E	781	34.31	633.1	30
7	8	119	45 24.0 N	159 35.7 E	0	32.99	495.8	30
7	8	119	45 24.0 N	159 35.7 E	5	33.01	497.5	30
7	8	119	45 24.0 N	159 35.7 E	22	33.02	501.4	30
7	8	119	45 24.0 N	159 35.7 E	45	33.06	503.7	30
7	8	119	45 24.0 N	159 35.7 E	72	33.14	514.6	30
7	8	119	45 24.0 N	159 35.7 E	90	33.12	512.8	30
7	8	119	45 24.0 N	159 35.7 E	97	33.20	520.7	30
7	8	119	45 24.0 N	159 35.7 E	183	33.77	576.1	30
7	8	119	45 24.0 N	159 35.7 E	230	33.93	592.2	30
7	8	119	45 24.0 N	159 35.7 E	277	34.02	601.9	30
13	14	122	46 16.3 N	174 03.0 E	0	32.81	483.3	30
13	14	122	46 16.3 N	174 03.0 E	22	32.87	487.3	30

Table 1. Titration comparisons used in calibration of salinity bridge--Concluded

Date		Sta-tion no.	Latitude	Longitude	Depth	Salinity by titration	Slide-wire reading	Nominal regulating temperature
Bridge	Titration							
1929	1929		° ′	° ′	m			°C
July 13	July 14	122	46 16.3 N	174 03.0 E	45	33.04	505.3	30
13	14	122	46 16.3 N	174 03.0 E	67	33.09	509.6	30
13	14	122	46 16.3 N	174 03.0 E	90	33.12	512.0	30
13	14	122	46 16.3 N	174 03.0 E	135	33.21	519.2	30
13	14	122	46 16.3 N	174 03.0 E	182	33.41	543.5	30
13	14	122	46 16.3 N	174 03.0 E	273	33.79	581.9	30
13	14	122	46 16.3 N	174 03.0 E	365	33.98	602.3	30
13	14	122	46 16.3 N	174 03.0 E	460	34.12	614.0	30
19	20	125	51 57.7 N	150 38.7 W	0	32.75-	474.5	30
19	20	125	51 57.7 N	150 38.7 W	5	32.74+	473.4	30
19	20	125	51 57.7 N	150 38.7 W	24	32.73	471.8	30
19	20	125	51 57.7 N	150 38.7 W	46	32.79	478.6	30
19	20	125	51 57.7 N	150 38.7 W	66	32.84	481.6	30
19	20	125	51 57.7 N	150 38.7 W	175	33.85	583.9	30
25	26	128	40 36.8 N	132 23.3 W	1093	34.41	645.7	30
25	26	128	40 36.8 N	132 23.3 W	1655	34.47	651.2	30
25	26	128	40 36.8 N	132 23.3 W	2180	34.60	658.9	30
Sep. 10	Sep. 11	133	29 20.7 N	132 30.0 W	0	34.71	671.6	30
10	11	133	29 20.7 N	132 30.0 W	23	34.73	680.9	30
10	11	133	29 20.7 N	132 30.0 W	93	34.77	678.2	30
10	11	133	29 20.7 N	132 30.0 W	279	33.96	597.7	30
10	11	133	29 20.7 N	132 30.0 W	373	33.98	607.1	30
10	11	133	29 20.7 N	132 30.0 W	581	34.09	611.9	30
10	11	133	29 20.7 N	132 30.0 W	2739	34.62	665.3	30
10	11	Evaporimeter sample				37.69	760.3	30
10	11	Evaporimeter sample				33.59	565.7	30
10	11	Evaporimeter sample				37.05	891.7	30
16	17	136	26 12.7 N	142 02.5 W	0	35.36	734.5	30
16	17	136	26 12.7 N	142 02.5 W	48	35.13	712.4	30
16	17	136	26 12.7 N	142 02.5 W	95	34.99	701.3	30
16	17	136	26 12.7 N	142 02.5 W	663	34.15	618.7	30
16	17	Evaporimeter sample				38.22	994.6	30
16	17	Evaporimeter sample				35.25	722.1	30
Oct. 9	Oct. 10	143	34 05.9 N	157 08.7 W	0	34.43	641.8	30*
9	10	143	34 05.9 N	157 08.7 W	4	34.42	641.5	30*
9	10	143	34 05.9 N	157 08.7 W	20	34.44	644.0	30*
9	10	143	34 05.9 N	157 08.7 W	40	34.39	643.2	30*
9	10	143	34 05.9 N	157 08.7 W	56	34.19	619.1	30*
9	10	143	34 05.9 N	157 08.7 W	163	34.20	622.7	30*
9	10	143	34.05.9 N	157 08.7 W	506	33.98	602.3	30*
9	10	143	34 05.9 N	157 08.7 W	722	34.09	609.2	30*
9	10	143	34 05.9 N	157 08.7 W	1877	34.59	657.1	30*
15	16	146	31 50.9 N	140 49.6 W	22	34.86	687.9	30
15	16	146	31 50.9 N	140 49.6 W	469	34.01	603.0	30
15	16	146	31 50.9 N	140 49.6 W	665	34.04	611.2	30
15	16	146	31 50.9 N	140 49.6 W	764	34.23	625.8	30
15	16	146	31 50.9 N	140 49.6 W	1096	34.42	646.0	30
15	16	146	31 50.9 N	140 49.6 W	1650	34.53	656.1	30
15	16	146	31 50.9 N	140 49.6 W	2173	34.60	661.9	30
27	28	152	10 04.9 N	139 43.6 W	0	33.67	568.7	40
27	28	152	10 04.9 N	139 43.6 W	24	34.51	651.3	40
27	28	152	10 04.9 N	139 43.6 W	188	34.70	672.3	40
27	28	152	10 04.9 N	139 43.6 W	283	34.68+	670.0	40
27	28	152	10 04.9 N	139 43.6 W	472	34.61	661.0	40
27	28	152	10 04.9 N	139 43.6 W	583	34.56	656.4	40
27	28	152	10 04.9 N	139 43.6 W	870	34.53	654.4	40
27	28	152	10 04.9 N	139 43.6 W	2948	34.67	677.5	40
27	28	152	10 04.9 N	139 43.6 W	3923	34.68-	666.3	40
Nov. 8	Nov. 9	158	6 33.1 S	154 58.4 W	0	35.57	752.3	40
8	9	158	6 33.1 S	154 58.4 W	24	35.57	754.0	40
8	9	158	6 33.1 S	154 58.4 W	73	35.66-	760.9	40
8	9	158	6 33.1 S	154 58.4 W	96	35.85	780.5	40
8	9	158	6 33.1 S	154 58.4 W	193	35.66-	762.8	40
8	9	158	6 33.1 S	154 58.4 W	2260	34.62	660.1	40
15	16	161	12 03.6 S	164 57.4 W	0	35.52	746.1	40
15	16	161	12 03.6 S	164 57.4 W	24	35.62	754.5	40
15	16	161	12 03.6 S	164 57.4 W	48	35.64	758.1	40
15	16	161	12 03.6 S	164 57.4 W	72	35.79	770.4	40
15	16	161	12 03.6 S	164 57.4 W	96	36.04	791.9	40
15	16	161	12 03.6 S	164 57.4 W	146	36.20	808.9	40
15	16	161	12 03.6 S	164 57.4 W	191	35.92	783.1	40
15	16	161	12 03.6 S	164 57.4 W	286	35.14	709.7	40

* Bridge values considered unreliable because of large differences between initial and final standards

the date of measurement to determine whether or not there had been any change in the bridge calibration which might have been caused by differential aging among the end coils and slide wire or by corrosion. As the differences were not systematic with respect to time, no corrections for time were applied.

These differences were then plotted against their respective salinities as given by equation (2). In this case systematic differences were found and a smooth curve drawn through them. The departures of this curve from zero were then tabulated as corrections to be applied to the salinities determined from the slide-wire readings by means of equation (2). These corrections, given in table 2, are largely attributable to irregularities in the slide wire. The alternative assumption is that these differences arise from variation in composition of the salt, and such an assumption would require that the composition be an irregular function of the salinity. Such a relation seems highly improbable. When these corrections are applied to the salinities derived from equation (2), of the 219 comparisons, 212 differ from the titration values by amounts equal to or less than 0.04 per mille salinity. This seems to show an even greater constancy of salt composition than has been assumed in the past and leads one to question the accuracy of chemical analyses of sea water as published in the past. Such published analyses indicate that if solutions of each were adjusted to equal concentration, the salinities as given by titration would differ in some cases in the first decimal place of parts per thousand. Obviously no such variations were encountered in the cruise of the Carnegie.

As a routine matter the samples of sea water collected at an oceanographic station in the morning were transferred, on arrival at the surface, to glass bottles of the citrate-of-magnesia type. These bottles were of about 350-cc capacity and were equipped with patent rubber washer stoppers. The same glass bottles were used repeatedly and were used only for sea water. The rubber washers were replaced as often as their deterioration required. To guard further against evaporation, dilution, or contamination of the samples, their salinities were measured on the afternoon of the same day they were collected.

The covers were removed from the salinity bridge and the stirring motor and thermostatically controlled heaters of the water bath were set in operation about an hour before measurements were started, in order to have equilibrium conditions of temperature established. The salinity bridge had three measuring cells, any one of which could be switched into the bridge circuit. The auxiliary cell had in series with it a small adjustable wire-wound resistance which will be called Q for convenience. The first step was to exhaust the measuring cells of the water which had been standing in them and to fill them with standard water after rinsing them with some of the same standard water. The sealed glass tubes of Copenhagen standard water were opened only as needed and their contents transferred to a glass-stoppered stock bottle. Any standard water remaining in the stock bottle from a previous run was used only for rinsing, the cells being filled with water from newly opened tubes. The time of filling each cell was then recorded. Fifteen minutes after the first cell was filled with standard water, the slide wire was set at a reading corresponding to the salinity of the standard water and the bridge balanced by adjusting Q. This adjustment was then tested by moving the slide wire and rebalancing the bridge by adjusting the slide wire. The setting of Q was correct if the slide wire was brought back to its original setting to balance the bridge. This reading of Q was then recorded for this particular cell, the standard water was removed from the cell which was then rinsed and filled with water from one of the samples to be measured. Record was made of the time of filling and the identity of the sample which took its designation from the number on the glass bottle in which it had been stored. Then the adjustment of Q was determined for the second cell, which in turn was filled with water to be tested. A similar procedure was followed for the third cell. Fifteen minutes after the unknown was placed in the first cell, Q was set to the reading previously obtained for that cell, the cell was switched into the circuit, and the bridge balanced by the adjustment of the slide wire. This slide-wire reading was recorded and the sample withdrawn from the cell, which was then rinsed and filled with water from another sample. The time of filling was again recorded and similar operations performed with the other cells until all the samples had been measured. As the last sample in each cell was removed, it was replaced by standard water. This standard water was measured exactly as if it were an unknown sample. The difference between the slide-wire reading for this final standard and its correct value (that for the initial standard) represented changes in the cells, changes in the solution in the auxiliary cell, or errors in the measurement of

Table 2. Corrections to be applied to salinities computed from second degree equation

| Computed salinity | | Correction |
From	To	
o/oo	o/oo	o/oo
....	33.03	±0.00
33.04	33.23	0.01
33.24	33.61	0.02
33.62	33.68	0.01
33.69	33.75	±0.00
33.76	33.83	- 0.01
33.84	33.96	- 0.02
33.97	34.15	- 0.03
34.16	34.44	- 0.02
34.45	34.55	- 0.01
34.56	34.63	±0.00
34.64	34.71	- 0.01
34.72	34.85	- 0.02
34.86	34.98	- 0.01
34.99	35.15	±0.00
35.16	35.27	0.01
35.28	35.68	0.02
35.69	35.77	0.03
35.78	36.08	0.04
36.09	36.15	0.03
36.16	36.20	0.02
36.21	36.24	0.01
36.25	36.28	±0.00
36.29	36.32	- 0.01
36.33	36.57	- 0.02
36.58	36.90	- 0.01
36.91	37.30	±0.00
37.31	37.69	0.01
37.70	38.10	0.02
38.11	....	0.03

either the initial or final standards. In the absence of any evidence to the contrary, it was assumed that this difference was the result of a gradual change and the difference was therefore proportioned according to the number of samples measured in the cell. After this shearing correction was applied to the slide-wire readings, they were converted to salinities by means of the previously discussed equation and corrections. The final standards were allowed to remain in the measuring cells until the bridge was used again. A specimen set of observations and computations is shown in table 3.

The design feature of having similar electrolytic cells form two adjacent arms of the bridge has, as one of its objectives, lessening the importance of accurate temperature control. In other words, it was hoped that by this device the effective temperature coefficient of the instrument would be much less than that of sea water. The efficacy of this arrangement was tested on the _Carnegie_ as follows: When the regulating temperature of

the water bath was changed from 30° to 40° C., Copenhagen standard water, which was used as the final standard at the end of the last 30° C routine salinity run, was left in the cells and was remeasured on the following day at 40° C, with the auxiliary resistance Q having the same setting as was used at 30° C. The differences in slide-wire readings were converted into differences in salinity and considered to be the effect produced by a 10° C change in temperature of a sample. This was done on a basis of 1.0 unit on the slide wire corresponding to a change of 0.01 per mille in salinity. This procedure further was based on the assumptions that during the period of about 24 hours the salinity of the solution in the auxiliary or Y cell did not change and that the cell constants did not change. Such assumptions were justifiable as only a rough determination was made. The slide-wire reading at the balance of the initial standard was 698.5 in each case, by definition. Either because of changes in cell constants or changes in the auxiliary cell

Table 3. Specimen set of observations and computations of salinity

Sample no.	Time	Q	Observed S. W. reading	Shearing correction	Corrected S. W. reading	Salinity from equation	Correction	Final salinity, o/oo	Depth in meters
				Cell A					
....[a]	1:56	1.124	698.5	....	....	....	......	....	......
227	2:14	1.124	645.7	+ 0.1	645.8	34.45	- 0.01	34.44	933
226[b]	2:36	1.125	628.8	+ 0.3	629.1	34.28	- 0.02	34.26	649
104	2:55	1.124	664.5	+ 0.4	664.9	34.65	- 0.01	34.64	3189
121[c]	3:14	1.124	696.3	+ 0.6	696.9	34.97	- 0.01	34.96	23
105	3:32	1.124	697.6	+ 0.7	698.3	34.99	±0.00	34.99	94
119[d]	3:51	1.124	654.2	+ 0.9	655.1	34.54	- 0.01	34.53	377
....[a]	4:08	1.124	697.5	....	....	....	....	....	......
			698.5						
			7⌊1.0						
			+0.1 3/7						
				Cell B					
....[a]	1:58	2.016	698.5	....	....	....	......	....	......
114	2:20	2.016	660.5	- 0.1	660.4	34.60	±0.00	34.60	1888
123[e]	2:38	2.016	658.0	- 0.2	657.8	34.57	±0.00	34.57	1412
101	2:59	2.016	699.8	- 0.3	699.5	35.00	±0.00	35.00	0
134	3:17	2.016	698.0	- 0.4	697.6	34.98	- 0.01	34.97	46
111	3:36	2.016	702.7	- 0.5	702.2	35.03	±0.00	35.03	187
113	3:54	2.016	635.9	- 0.6	635.3	34.34	- 0.02	34.32	473
....[a]	4:14	2.016	699.2	....	....	....	....	....	......
			698.5						
			7⌊0.7						
			-0.1						
				Cell C					
....[a]	2:04	2.940	698.5	....	....	......	......	....	......
335	2:26	2.940	680.0	- 15.8	664.2	34.64	- 0.01	34.63	2765
401[f]	2:41	2.940	697.7	- 15.8	663.9	34.63	±0.00	34.63	2335
274	3:02	2.940	711.3	- 15.8	695.5	34.96	- 0.01	34.95	5
115	3:20	2.940	718.5	- 15.8	702.7	35.03	±0.00	35.03	70
347[g]	3:39	2.940	695.5	- 15.8	679.7	34.80	- 0.02	34.78	281
110	3:56	2.940	645.4	- 15.8	629.6	34.29	- 0.02	34.27	666
....[a]	4:18	2.940	714.3	- 15.8	....	....	....	....	......
			698.5[h]						
			-15.8						

[a] Copenhagen standard water.   [b] 34.25 per mille by titration by J. H. P., May 28, 1929.   [c] 34.99 per mille by titration by J. H. P., May 28, 1929.   [d] 34.53 per mille by titration by J. H. P., May 28, 1929.   [e] 34.55 per mille by titration by J. H. P., May 28, 1929.   [f] 34.64 per mille by titration by J. H. P., May 28, 1929.   [g] 34.79 per mille by titration by J. H. P., May 28, 1929.   [h] Initial standard discarded as being probably in error.

solutions, the slide-wire readings were slightly different for the final standard than for the initial standard. If it is assumed that these changes were permanent, the slide-wire readings for the final standard should be used whereas if these changes are assumed to have been tem porary and to have disappeared (such as might be the case if part of the auxiliary cell solution vaporized dur- ing the run and condensed again afterward), then the slide-wire readings of the final standard should be used. Following the remeasurement of the final standards at 40°C, they were withdrawn and replaced by other sam- ples originally having the same salinity, and another series of slide-wire readings taken. Assuming that no change in salinity of the final standards had occured, the final standard as remeasured should be used. If it be assumed that the final standard had changed in salin- ity, then the fresh standard should be used. Thus there are four combinations per cell which will give a temper- ature coefficient of salinity. Their means have been taken as shown in table 4.

These temperature coefficients, even if accurately determined, would only apply with the same settings of the auxiliary resistance Q. As the settings given above approximately represent ohms and as the resistance of the cells were about 250 to 300 ohms each, it is seen that the uncompensated sea-water resistance was about 1 per cent of the resistance of the unknown. Taking the temperature coefficient of electrical conductivity of sea water as 3 per cent per degree centigrade, the tempera- ture coefficient of salinity of the bridge would have been expected to be of the order of 0.0003×35.00 or about 0.01 per mille per degree centigrade. The general agreement between the experimental and calculated val- ues indicates that the temperature coefficient of the bridge arm containing the Y cell differed from that of the arm containing the X cell by not more than 3 parts in 10,000. This would not be true generally, but would depend on the difference in cell constants of the X and Y cells and on the ratio of the resistance of Q to the re- sistance of the sea water in the Y cell. It may be noted, however, that had a wire resistance been used in place of sea water in the Y cell, the temperature coefficient would have been in the neighborhood of 0.03×35 or about

1 per mille per degree centigrade. It should be under- stood that the wire resistances in the bridge were of manganin, having a negligible temperature coefficient, and that when measurements were made the X and Y cells were accurately at the same temperature.

Copenhagen standard water was used at every third station, substandards being used at the intermediate sta- tions. At a station where Copenhagen water was used, three large samples were taken, measured, and the sur- plus kept until the next station (usually two days later), when they were used as standards in the same manner as the Copenhagen water was used. At this second sta- tion large samples were again measured for use as standards at the third station. At the next succeeding station, Copenhagen water was again used and the cycle repeated. It will be seen then that the possible errors of a single determination of salinity at successive sta- tions are 1, 2, and 3 times the error of a single deter- mination made at a station where Copenhagen standard water was used. The bridge could be balanced to about 0.002 per mille salinity but the accuracy of the measure- ment was not as great as this precision because of the uncertainty of the resistance Q, errors in the assump- tion that a shearing correction compensated for the dif- ference between initial and final standards, and other minor factors such as unequal heating caused by the test current. Individual measurements were therefore accurate to within about 0.02 per mille salinity in terms of that of the standard used. Thus, if the salinity of the Copenhagen standard water was accurately known, meas- urements against such a standard were good to about 0.02 per mille salinity. Consequently it is possible that at stations where a first substandard was used the meas- urements might have been in error by 0.04 per mille and at stations where a second substandard was used an er- ror of 0.06 per mille was possible. This is highly im- probable, however, inasmuch as such a situation would require all the errors to be made in the same direction and, as three different cells were used for the measure- ment of samples from each station, such discrepancies would probably have been detected in plotting vertical distribution curves, unless the standards for all three cells were in error by similar amounts and in the same

Table 4. Data for temperature coefficients of salinity for cells A, B, and C

Cell	Obser- vation	Temper- ature	Standard	Q	Slide-wire reading	Temperature coefficient	
						From	Value
		°C			d		°/oo per °C
A	I	30	Initial	1.913	698.5	I and III	0.0078
	II	30	Final	1.913	698.1	I and IV	0.0047
	III	40	Final	1.913	706.3	II and III	0.0082
	IV	40	New	1.913	703.2	II and IV	0.0051
Mean for cell A	...	...	....	....	....	....	0.0064
B	I	30	Initial	3.048	698.5	I and III	0.0041
	II	30	Final	3.048	698.2	I and IV	0.0067
	III	40	Final	3.048	702.6	II and III	0.0044
	IV	40	New	3.048	705.2	II and IV	0.0070
Mean for cell B	...	...	....	....	....	....	0.0056
C	I	30	Initial	3.208	698.5	I and III	0.0138
	II	30	Final	3.208	698.7	I and IV	0.0116
	III	40	Final	3.208	712.3	II and III	0.0136
	IV	40	New	3.208	710.1	II and IV	0.0114
Mean for cell C	...	...	....	....	....	....	0.0126

direction for each station. The best criterion of the errors involved in these measurements is the scatter of measured values of salinity of the deep water of the Pacific. A composite graph showing such salinity values from a number of stations when plotted against depth is given in figure 2. All measured values from stations 130 to 149 inclusive and from depths below 1800 meters are shown in this figure. The figures opposite the points give the number of the oceanographic station at which the sample was collected and those which are underlined represent stations at which Copenhagen standard water was used. It will be noticed that below 2000 meters only

two points depart from the smooth curve by as much as 0.04 per mille. This particular group of stations has been selected as an illustration because it is one of the largest groups in which the deep water has similar characteristics. Other groups show equally good agreement between stations within a group. From these considerations it is concluded that the salinities determined on the Carnegie are reliable to about 0.04 per mille. The results of the salinity work are given in the table giving the data obtained at the series stations (table 2, I-B), and the vertical distribution curves are shown in the graphs preceding the tables.

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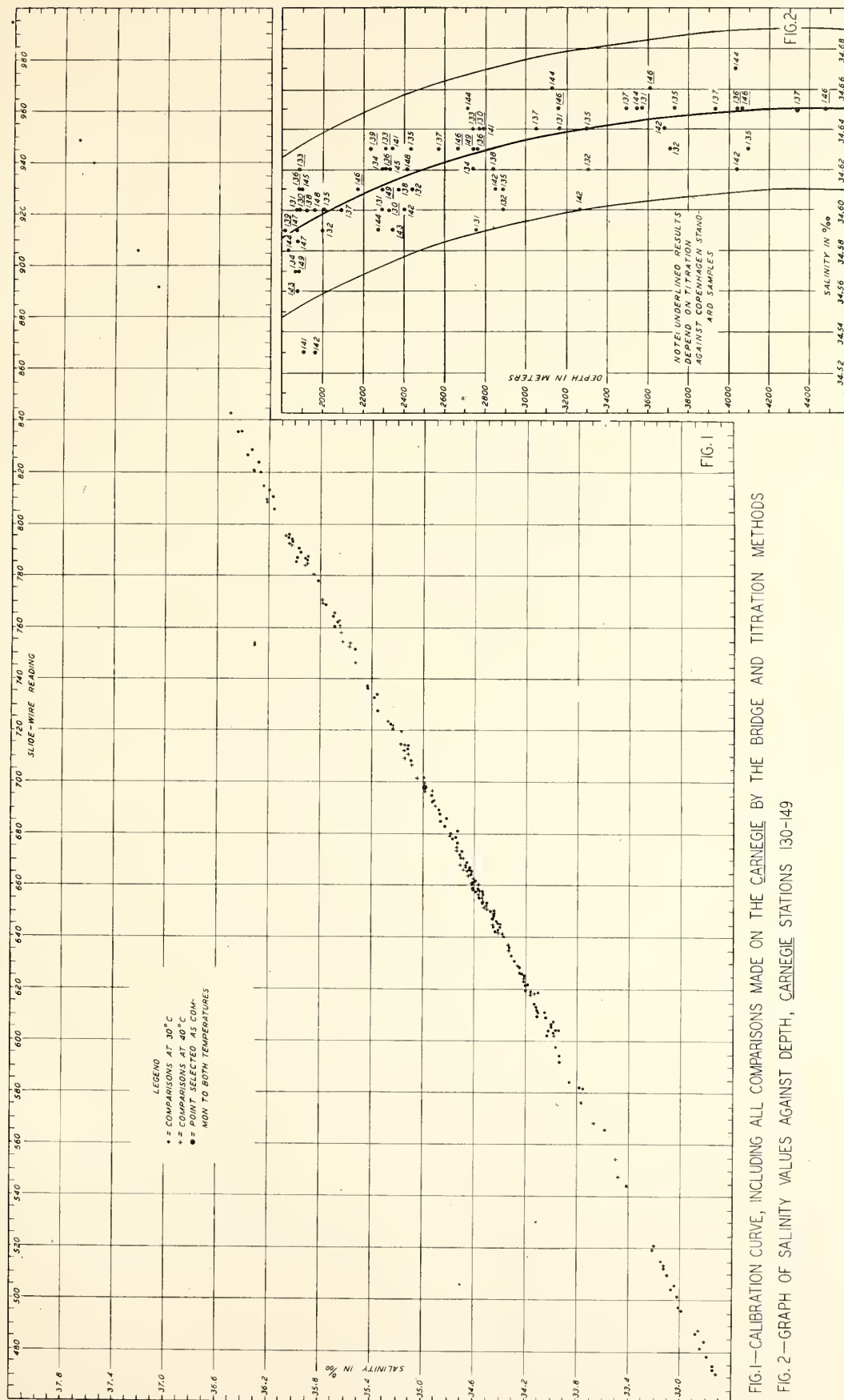
FIG. I.—CALIBRATION CURVE, INCLUDING ALL COMPARISONS MADE ON THE CARNEGIE BY THE BRIDGE AND TITRATION METHODS

FIG. 2.—GRAPH OF SALINITY VALUES AGAINST DEPTH, CARNEGIE STATIONS 130-149

In the preceding chapter Soule has shown that the readings of the salinity bridge were converted into terms of salinity by means of a calibration curve which was obtained by measuring samples in the bridge and titrating the same samples by the ordinary silver-nitrate method. Owing to this procedure the salinities obtained from bridge readings should, on an average, be equal to salinities determined by titration, but the accidental errors of the values would be somewhat greater, amounting to ± 0.04 per mille, mainly since minor deviation from a constant temperature exercised a considerable influence on the bridge readings. A comparison between the Carnegie salinities and those from other expeditions indicates, however, that the Carnegie salinities are, on an average, somewhat too low. This result is arrived at by a study of the conditions at great depths where the salinity is very uniform and where no variations from year to year have been detected.

In his discussion of the deep water of the North Atlantic Wüst (1935) writes (in translation): "In our salinity charts at 1500 to 4500 meters the Carnegie salinities in the open North Atlantic Ocean appear to be on an average 0.03 to 0.04 per mille too low, as also shown from a comparison between the TS-curves at the Carnegie stations and neighboring stations from other expeditions (in single cases the deviations of the Carnegie salinities vary between -0.10 and 0.02 per mille."

In the Pacific Ocean the salinity of the deep water has been determined on two later expeditions, the Dana expedition in 1928 to 1930, and the Bushnell in 1934. The Dana observations have not been communicated in detail, but some of them have been used in special publications. In Schott's (1935) "Geographie des Indischen und Stillen Ozeans," salinities and temperatures are given at the depth of 3000 meters at a station in latitude 20° south and longitude 174° east, and at depths of 3000, 4000, and 5110 meters at a station in latitude 19° south and longitude 163° west. These values can be compared with Carnegie observations at depths greater than 3000 meters at stations 87 to 91 which are located between latitudes 15° and 18° south and longitudes 145° and 160° west. We find:

Stations	Lati- tude, °S	Longi- tude °W	Mean depth m	Mean temp. °C	Mean salinity °/oo	No. ob- serva- tions
Dana	19-20	163-186	3775	1.558	34.680	4
Carnegie	15-18	145-160	3357	1.599	34.653	7

The U.S.S. Bushnell undertook oceanographic work in the North Pacific, occupying eighteen stations between Adak, Aleutian Islands and Oahu, Hawaiian Islands, to depths of 2500 to 3500 meters. The observations[1] below 3000 meters can be compared with the Carnegie observations below 3000 meters at stations 122, 142, 144, and 146, of which station 122 is located near the Aleutian Islands and stations 142, 144, and 146 nearer the Hawaiian Islands. We obtain the following table.

Stations	Lati- tude °N	Longi- tude °W	Mean depth m	Mean temp. °C	Mean salinity °/oo	No. ob- serva- tions
Bushnell	50-22	158-170	3396	1.501	34.675	13
Carnegie	46-32	140-174	3637	1.528	34.644	11

If we consider 34.67 as the characteristic salinity of this region we find that the single Carnegie salinities deviate from -0.07 to 0.00 per mille from this value. Thus, the range of variation is less than in the North Atlantic, indicating that the accuracy of single determinations was greater during the latter part of the cruise than during the first part.

Compiling these different comparisons we obtain the following differences between the salinity of the deep water as determined on other expeditions and on the cruise of the Carnegie:

North Atlantic	South Pacific	North Pacific
0.03 to 0.04	0.027	0.031

From the systematic character of these differences we must conclude that the Carnegie values of the salinity of the deep water are about 0.03 per mille too low. It follows that all salinity values between 34.6 and 35.0 per mille are too low by the same amount, but it has not been possible to find the cause of this systematic discrepancy, nor has it been possible to decide whether or not a similar discrepancy is present at other values of the salinity.

All tables and graphs had been prepared in final form before this systematic discrepancy was discovered, for which reason the original Carnegie values have not been changed, but in the text attention has been drawn to the discrepancy in all cases in which the exact value of the salinity of the deep water has been discussed.

It may be added that the discrepancy will not influence the results of the dynamic computations, if it has the character of a constant difference, but if the difference depends on the absolute value of the salinity, an error is introduced in the results of such computations. This error will not be serious since it will only influence the data from the upper layers and will no doubt be smaller than uncertainties arising from lack of knowledge as to periodic or aperiodic variations in these layers.

[1] These were kindly placed at the author's disposal by the Scripps Institution of Oceanography.

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The bottom samples were collected with samplers attached to the end of a hemp lead line which in turn was attached to the end of a steel piano wire carried on one of the winch drums and led over a meter-wheel at the stern of the vessel. The striking of bottom by the sampler was determined manually by keeping tension in the outgoing piano wire with a roller bar.

Most of the samples were taken with a snapper-type sampler--the sample being caught in a spring-actuated clamshell. The snapper-type samplers used varied considerably in size, type of trigger, and design of weight, but after considerable experimentation, the type selected as most suitable to the equipment and conditions existing on the Carnegie was that shown in figure 1. Here the pear-shaped lead weight was counterbored to fit down over the spring, thus lowering the center of gravity. Later the lead weight was so arranged as to be left on bottom in order to reduce the strain on the wire when hauling in. This was done as follows. The weights were cast in halves containing staples in their upper ends. When placed on the shank of the snapper they were tacked together by a flat copper staple on each side near the bottom of the weight. A wire whose ends were made fast to the upper staples passed over the hook of a Sigsbee releasing device and held the upper ends of the weight together. When the sampler struck bottom, the Sigsbee device released the wire, the upper ends of the

weights fell apart tearing loose the lower staples and the two halves fell clear of the snapper and were left on the bottom.

This type of snapper was of sufficient size to yield about one and one-quarter liters of sample when the bottom was of ooze, mud, or clay. On striking hard bottom it usually collected only a few fragments and the jaws were badly dented and had to be repaired. Nodules, cinders, fragments of obsidian, and similar hard obstructions were sometimes caught between the jaws, thus permitting the rest of the sample to be washed out on the way to the surface.

A tube sampler intended to give a core sample and used on the Meteor was used a few times. It is shown in figure 2. This sampler was lined with a removable glass tube so that the sample could be inspected and stored while still in the lining tube. This type of sampler was not used more frequently because of its considerably greater weight and the pull required to withdraw it from the bottom put too heavy a strain on the piano wire.

The core samples obtained were stoppered in their lining tubes and the samples obtained with snappers were transferred to glass bottles and stoppered soon after collection. They were then shipped to Washington from the next port into which the Carnegie went.

FIG. I—SNAPPER-TYPE BOTTOM SAMPLER WITH COUNTERBORED LEAD WEIGHT
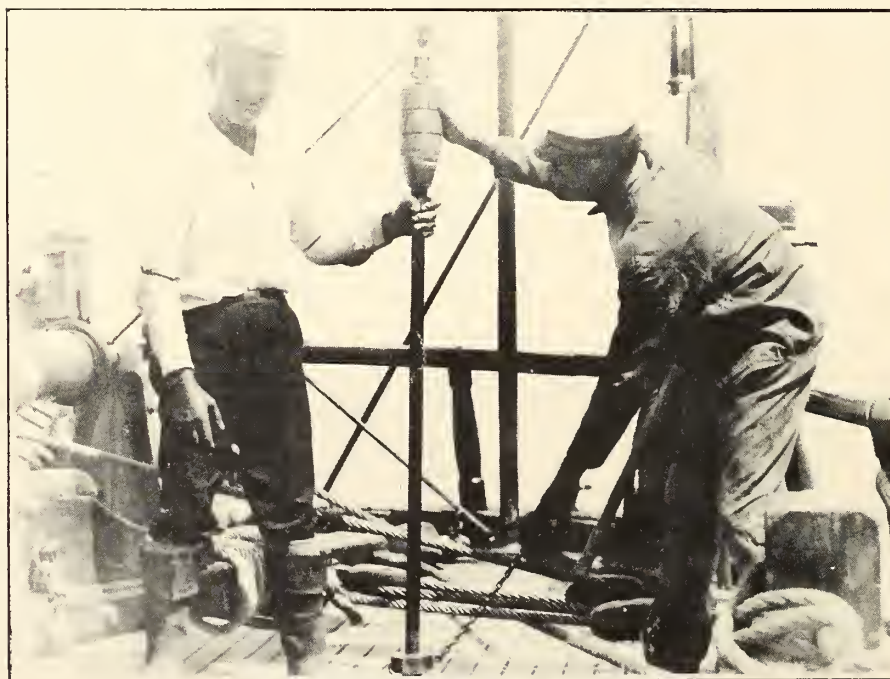
FIG. 2—<u>METEOR</u> TUBE BOTTOM SAMPLER

OBSERVATIONS AND RESULTS IN PHYSICAL OCEANOGRAPHY

II

RESULTS IN PHYSICAL OCEANOGRAPHY

CONTENTS

INTRODUCTION

The present paper was prepared in 1930 to 1931, and revised in 1936. In the years 1930 to 1936 a considerable amount of new data was accumulated from the Pacific Ocean. This has not been incorporated in the present discussion, since such procedure would have altered the entire plan of the publication. The only chapter which has been rewritten to some extent is the one dealing with the origin of the deep water of the Pacific, because recent information as to the circulation around the Antarctic Continent has thrown considerably more light on this question and has made more definite conclusions possible.

The writer takes great pleasure in acknowledging the assistance which he has received from members of the staff of the Department of Terrestrial Magnetism, especially from C. C. Ennis, who undertook a great number of the computations, prepared all figures, and in the course of this work made a number of valuable suggestions.

It will be readily realized that the careful reduction of the extensive observations made during the cruise is of paramount importance in any discussion of the results within physical oceanography. The original computations, compilations, and graphs of this observed material were completed under the general direction of J. A. Fleming by Martha W. Ennis, C. C. Ennis, W. C. Hendrix, and S. L. Seaton, Jr. It will be realized that in the course of this work they all made valuable suggestions which have been incorporated and made use of in the present discussion. It will be noted that the general results of the discussion are represented in figures 1 to 38 which follow the text. The graphs of observational material above referred to are independently numbered as figures 1 to 254 and are reproduced in Oceanography I-B. In the text the graphs are referred to as, for example, (fig. 1, I-B).

THE NORTH ATLANTIC OCEAN

Temperature, Salinity, and Density

The physical oceanography of the North Atlantic Ocean has been treated by several authors (Jacobsen, 1929; Helland-Hansen, 1930; Helland-Hansen and Nansen, 1926; and Wüst, 1928) on the basis of modern observations. In the following discussion it will be shown that the results of the Carnegie observations on the whole are in agreement with the previous conceptions as to the physical properties of the waters of the North Atlantic and as to the character of the circulation. Details will be given in only a few cases in which the Carnegie observations throw more light on the problems.

Temperature and Salinity, Stations 1 to 12.--The distances between stations 1 to 12 are so great that the results cannot be used for construction of sections; therefore, the data from the single stations will be discussed separately. Station 1 was in the region of the warm water of the Gulf Stream. The vertical distribution of salinity and temperature was very much like the distribution at station 16, which is located in nearly the same latitude but 21° farther east. Even the vertical changes of pH and PO_4 were similar at the two stations.

Station 2 reached to 400 meters only, and down to this depth there existed a striking similarity to station 15, which was taken in nearly the same locality three months later. It should be noted that the distance to station 16 from station 15 is not much greater but at this station the conditions in the upper 400 meters deviated considerably from those at station 2.

The distances between stations 3, 4, and 5 are small, nevertheless the vertical distribution of temperature and salinity at these stations differed considerably. Station 4 reached to 300 meters only, and down to that depth showed lower temperatures and lower salinities than the two neighboring stations. The difference between stations 3 and 5 was especially great at the depths between

500 and 1500 meters, where the temperature and salinity were higher at station 5 than at station 3. The differences in the density, σ_t, therefore, had a maximum at about 700 meters, as shown in table 1.

Station 6, which is located to the southwest of Ireland, showed still higher temperatures and salinities at depths 1000 and 1500 meters. The temperature and salinity at 1000 meters, $8°50$ and 35.52 per mille, respectively, appear very high, but the Michael Sars, station 93, (Helland-Hansen, 1930) gave $8°27$ and 35.47 per mille on July 25, 1910 in nearly the same locality.

Stations 7 and 8 are located to the east-southeast of Iceland; the former on the Iceland-Faroe Ridge, the latter on the shelf surrounding Iceland. At the latter station water of Atlantic character--high temperature and high salinity--was found to a depth of more than 700 meters, whereas at the former the Atlantic water reached from the surface down to 200 meters, but the characteristic water of the Norwegian Sea was met with at the bottom, 454 meters.

Table 1. Comparison of values of density, σ_t, at Carnegie stations 3 and 5, 1928

Depth in meters	Density, σ_t		Difference (3 - 5)
	Station 3	Station 5	
0	26.69	26.66	+0.03
100	26.96	26.98	-0.02
200	27.03	27.04	-0.01
300	27.05	27.06	-0.01
400	27.11	27.08	+0.03
500	27.20	27.10	+0.10
700	27.41	27.18	+0.23
1000	27.67	27.58	+0.09
1500	27.78	27.77	+0.01
2000	27.81	27.78	+0.03

At station 9, to the southwest of Iceland, water of a relatively high temperature and salinity was still found, but at stations 10 and 11 low temperatures were present below a depth of 75 or 100 meters, and salinities above 35 per mille occurred only at some levels above 200 meters.

At station 12 the temperature was still lower, namely $3°60$ at 75 meters, decreasing to $3°30$ at 500, $3°10$ at 1000, and $2°75$ at 2000 meters, whereas the salinity remained practically constant and equal to 34.87 per mille, perhaps increasing slowly with depth below 500 meters. The density in situ was almost constant between 75 and 100 meters, varying between 27.74 and 27.77, but below 700 meters it increased slowly to 27.86 at 2500 meters.

The uniform character of the water in the region of station 12 has been pointed out by Matthews and considered by Jacobsen (1929), who especially discussed the opinion of Nansen regarding the origin of the deep water of the Western Atlantic Basin. Nansen had indicated that the region southeast of Greenland is a place where this deep water is formed, because cooling of the surface layers in winter may give rise to convective currents, which, because of the uniform character of the water, may reach to great depths. Jacobsen, however, arrives at the result that these processes probably contribute to the formation of the uniform water north of the Grand Banks of Newfoundland, whereas the true bottom water comes from the continental shelf in Denmark Strait.

Vertical Sections

The most important results of the work of the Carnegie in the Atlantic are represented in the two vertical sections I and II. Section I is based on the observations at stations 13 to 24 and shows a north and south section approximately along the meridian 40° west between latitudes 46° and 8° north. Section II is from the observations at stations 25 to 34 and shows an east and west section approximately along the parallel 12° north and between longitudes 37° and 79° west.

Section I.--Section I, comprising stations 13 to 24, is taken across the Atlantic Ridge, as is evident from the profile of the bottom. Station 13 is situated on the Grand Banks of Newfoundland; stations 14, 15, and 16 in the Western Atlantic Basin; stations 17 and 18 on the ridge; and the rest of the stations, from 19 to 24, are in the Eastern Basin.

The isotherms in Section I (fig. 94; I-B) show the well-known accumulation of warm water with its center at about latitude 30° north. Considering the rapid variation in temperature with the distance from the Grand Banks, a station on the slope of the Grand Banks would have been of value in order to establish the course of the isotherms. The double bend of the isotherms south of the Grand Banks indicates the existence of a whirl at the boundary between the cold water on the southern slope of the Grand Banks and the warmer water to the south. In this region, but in another location, a similar whirl is indicated by the Michael Sars section (Helland-Hansen, 1930), which runs a little to the west of the Carnegie section. It is probable that changing whirls of different dimensions are formed at the boundary of the Gulf Stream, for which reason the hydrographic conditions in a given locality may change rapidly. Our section, therefore, represents the conditions as observed by the Carnegie, but probably not any stationary conditions.

The isohalines in Section I (fig. 95; I-B) clearly show the great accumulation of water of high salinity with its center at about latitude 30° north. The isohaline 35 per mille reaches, at the center, to a depth of more than 2000 meters. The whirl to the south of the Grand Banks, which was indicated by the temperature distribution, is also shown by the course of the isohalines.

To the south the influence of the intermediate Antarctic Current is seen in the minimum of salinity at a depth between 500 and 1000 meters. The effect of this intermediate current reaches, according to the Carnegie, at least beyond station 20 or to about latitude 20° north, and perhaps can be traced as far as between stations 18 and 19, or about latitude 26° north.

At the surface the greatest salinity is found between stations 18 and 19, or between latitudes 24° and 30° north. From the course of the isohalines, it seems that water of very great salinity is spreading to the north and to the south at a level of about 100 meters. This water represents the type which Jacobsen (1929) has called "central water" in his discussion of the results of the Dana expedition 1920 to 1922. Jacobsen shows, in agreement with the Carnegie results, that at a level of about 100 meters this water is flowing away from the region in which it is being formed, the Sargasso Sea region.

The deep water appears to have a salinity slightly below 34.90 per mille in both the Western and Eastern basins, but the Carnegie values are probably 0.03 to 0.04 per mille too low.

The density curves in Section I (fig. 96; I-B) show especially that the difference in density between stations 15 and 16 reaches a maximum somewhere below the surface. When discussing the conditions at stations 3 and 5 (p. 30 and table 1), it was pointed out that the greatest difference in density was found at a depth of about 700 meters. Table 2 is the result of an examination of stations 15 and 16. Here we find a considerable difference in the upper layers, reversal of sign, and a new maximum at about 500 and 700 meters.

Table 2. Comparison of values of density, σ_t, at Carnegie stations 15 and 16, 1928

Depth in meters	Density, σ_t		Difference (15 - 16)
	Station 15	Station 16	
0	24.47	23.95	+0.52
100	26.28	25.94	+0.32
200	26.41	26.41	0
300	26.42	26.61	-0.19
400	26.44	26.80	-0.36
500	26.49	26.93	-0.44
700	26.77	27.25	-0.48
1000	27.30	27.58	-0.28
1500	27.73	27.77	-0.04
2000	27.79	27.80	-0.01

Section II.--Section II, stations 25 to 34, runs approximately east and west, following the parallel of about 12° north from 37° to 79° west longitude. It begins in the Eastern Basin of the Atlantic in which stations 25 and 26 are located, and continues across the ridge (with station 27 on the ridge), into the Western Basin in which stations 28, 29, and 30 are situated. It then crosses the threshold of the Caribbean Sea, in which the last four stations--31, 32, 33, and 34--are located.

At the surface the temperature (fig. 210; I-B) is uniform and high--between 25° and 30° C. In the Caribbean Sea we find in the upper layers a greater accumulation of warm water than in the Atlantic, the isotherms of 10° and 15° being found at greater depths in the Caribbean. The observations below a depth of 1000 meters in the Caribbean Sea indicate that below this depth the temperature remains almost constant. At all stations it decreases slightly with increasing depth, but the decrease is so slow that the deepest observation gives a temperature of 4°07 at a depth of 2287 meters, against 3°20 at the same depth outside the Caribbean Sea (station 30). The observations of the Dana in the Caribbean Sea (Jacobsen, 1929) give, on an average, a similar result, as is evident from table 3.

Table 3. Temperature below 1000 meters in the Caribbean Sea according to the Dana and the Carnegie

Source	Depth in meters		
	1000	1500	2000
	°	°	°
Dana (8 stations)	4.98	4.22	4.09
Carnegie (4 stations)	4.91	4.15	4.08

The observations at great depths by the Dana indicate a rise of the temperature from a level of 2000 or 2500 meters toward the bottom, corresponding approximately to adiabatic equilibrium.

In the Atlantic part of Section II the temperature decreases regularly toward the bottom, the lowest value observed being 2°17 at a depth of 4703 meters at station 30.

The salinity curves in Section II (fig. 101; I-B) show a maximum below the surface at a depth of about 100 meters. This maximum, as already pointed out by Jacobsen, is probably related to the existence of currents which carry salt water from the central part of the Atlantic Ocean to the south.

The salinity minimum at a level of about 700 meters, indicating the intermediate Antarctic Current, is clearly seen. It also is evident that this intermediate water penetrates the Caribbean Sea, but here it probably becomes mixed with the overlying and underlying water since the salinity of the intermediate water increases somewhat when proceeding to the west. These features have been treated thoroughly by Jacobsen, who especially has examined the mixing of the water masses of different origin.

The Carnegie observations indicate a decrease in the salinity of the water of the Caribbean Sea below a depth of 1000 meters, but this decrease is probably not a real feature in spite of the fact that it is shown by the observations at two stations, 33 and 34. At the former a salinity of 34.76 per mille was observed at a depth of 2075 meters, and at the latter a salinity of 34.74 per mille at 2287 meters. The observations of the Dana below a level of 1200 meters, however, show a uniform salinity varying between 34.95 per mille and 34.98 per mille. The observed values at the greatest depths of stations 33 and 34 therefore have been rejected and, instead, it was assumed that the salinity at a level of 2000 meters was 34.96 per mille at both stations. When carrying out the dynamic calculation this value was used.

The Deep Water of the Atlantic

Temperature.--Helland-Hansen (1930) has shown that the Challenger observations indicate that the bottom temperatures decrease with increasing depth in the Western Atlantic Deep, but increase in the Eastern Atlantic Deep. Introducing the potential temperature, θ, defined as the temperature which a water particle attains when it is raised adiabatically to the surface of the sea, he found that the potential temperature decreases with increasing depth in the Western Deep but remains constant in the Eastern Deep. The absolute values are lower in the Western Deep and this result is confirmed by the observations of the Dana.

We have table 4 as a result of an examination of the potential temperature of the water below a depth of 4000 meters according to the Carnegie observations. The data are too few to permit any conclusions as to the average conditions in the two basins, except that the potential temperature is lower in the Western Deep than in the Eastern. It may be added that all values in the Eastern Deep are lower than the average value, 2°15, found by Helland-Hansen from the Challenger observations.

Salinity.--Table 5 is the result of the observations of salinity below a level of 4000 meters. The salinity appears to be slightly lower in the Eastern Deep, but the values are too few and show too much scattering to permit any definite conclusions. The absolute values are, as stated on page 72, probably 0.03 to 0.04 per mille too low.

Table 4. Values of potential temperature, Atlantic deep water, Carnegie, 1928

Western deep			Eastern deep		
Station	Depth	θ	Station	Depth	θ
	m	°		m	°
14	4061	1.86	19	4091	2.10
				4616	2.03
				5148	1.96
15	4319	2.01			
	4841	1.90			
			21	4126	2.07
			23	4076	2.06
30	4703	1.73			
Mean	4481	1.88		4411	2.04

Table 5. Values of salinity, Atlantic deep water, Carnegie, 1928

Western deep			Eastern deep		
Station	Depth	S,	Station	Depth	S,
	m	°/oo		m	°/oo
14	4061	34.89	19	4091	34.87
				4616	34.80
				5148	34.83
15	4319	34.89			
	4841	34.85			
			21	4126	34.87
			23	4076	34.81
Mean	4407	34.88		4411	34.84

For comparison we add table 6 which shows the mean potential temperature and the salinity at an approximate depth of 4500 meters according to the observations of Challenger, Dana, and Carnegie.

Table 6. Mean potential temperature and salinity, Atlantic deep water, Carnegie, 1928

Source	Western deep		Eastern deep	
	θ	S	θ	S
	°	°/oo	°	°/oo
Challenger	2.00		2.15	
Dana	1.91 (16)	34.89 (17)	2.08 (9)	34.90 (9)
Carnegie	1.88 (4)	34.88 (3)	2.04 (5)	34.84 (5)

The number of observations are shown in parenthesis

The temperatures of the Challenger appear to be about 0°.1 too high. The Dana and Carnegie temperatures agree well, but the Dana salinities are 0.035 per mille higher on an average.

Temperature-Salinity Relation

The temperature-salinity (tS) diagrams, which were introduced by Helland-Hansen (1918), have proved very helpful in the discussion of the origin and the mixing of the different types of water in the oceans. The tS diagrams therefore have been plotted for each station.

Jacobsen (1929) has discussed the character of the waters of the North Atlantic by means of the tS diagrams from the Dana expeditions. A comparison shows that the data from the Carnegie are, on the whole, in good agreement with the data which Jacobsen discusses. A similar discussion therefore would not lead to any new conclusions. We have seen (pp.30,31) that we found rather different conditions at the neighboring stations 3, 5, 15, and 16, and it is of interest to examine the extent to which water of a similar character is met with at these stations.

In figure 1 the tS curves for these four stations have been plotted. It is seen that they all agree quite well and that no considerable deviations from an average normal tS relation occur. Below a depth of 700 meters, however, where the discrepancies between the stations are found, we find agreement between the conditions at stations 3 and 16, and from 1000 and 1500 meters we find agreement at stations 5 and 15. Therefore, it can hardly be doubted that the water of high salinity and high temperature which is found between 700 and 1500 meters at station 5 comes from the west. On the other hand, it is not very probable that we can trace a continuous flow of this water from the region of station 15 to the region of station 5, because station 3 falls between the two localities. It is more probable that in both localities we deal with whirls which develop at the boundary of the strong Atlantic Current.

For comparison the tS diagram for station 6 has been shown in the same figure. This curve has a widely different course and at the depth of 1000 meters the deviation from the normal tS relation is very great. According to Helland-Hansen and Nansen this deviation in the region of station 6 must be ascribed to the influence of the Mediterranean water. When discussing the data

from this station, it was pointed out that the high temperatures and salinities are, as a rule, found between 700 and 1500 meters in the region where the station was occupied.

We shall not enter any more into detail as to the tS relations, but shall draw attention to some major features. When discussing the vertical sections we saw that a marked difference exists between the Carnegie stations north and south of latitude 20° north. To the south of this latitude the characteristic salinity minimum of the intermediate Antarctic Current is found at all stations, but to the north of this latitude the salinity decreases toward the bottom without any intermediate minimum. The tS relation therefore is quite different at the stations north and south of latitude 20° north. In figure 2 the data for observations at stations north of 20° north and below a level of 100 meters have been plotted, using different designations for observations in the depth intervals 100 to 500, 500 to 1500, and below 1500 meters. It is seen that all values fall nearly on a mean curve. This agrees well with the corresponding curves which Helland-Hansen has derived from the observations on board the Michael Sars and the Armauer Hansen which are also shown in the diagram. A few values fall above the lines, and these originate from regions where the Mediterranean water is found.

Another feature of considerable interest is that in the northern Atlantic the occurrence of water of a certain tS relation is not restricted to certain intervals of depth. Water of high temperature and high salinity is found in the upper layers only, but in other localities in the upper layers one finds water which has the properties of the water between 500 and 1500 meters at other stations, or even the properties of the deep water. This feature indicates that a considerable vertical circulation exists within the area of the North Atlantic where the observations have been made and that the deep water may be mixed with water which has been at the surface.

To the south of latitude 20° the salinity minimum is plainly seen in the tS diagram in figure 3, which shows a much more pronounced stratification of the water. Water of a temperature above 12° is never found below 500 meters, of a temperature below 7° never above 500 meters, and of a temperature below 4° never above 1500 meters. Therefore, a direct transport of surface water down to the greatest depth does not take place in the region from which these observations originate. This result is self-evident because all the observations were taken in the tropics, but the stratification has been pointed out here because it will be shown that the corresponding stratification is more pronounced in the Pacific. Figure 4 shows the tS relation on a more open scale for depths below 1400 meters. Short vertical lines on the various curves designate the approximate limiting depths within which the respective temperature and salinity values were obtained. Such designation was not made in figure 3 on the curve for the North Atlantic (stations 1 to 19) because of the varying characteristics of the water and the relative meagerness of data for depths below 1000 meters.

The temperature-salinity diagrams for each station are shown in figures 201 to 209, I-B. Because of insufficient data, no further detailed discussion of the characteristic properties of the water at different levels and in different regions of the North Atlantic will be attempted.

Results of Dynamic Calculations

Helland-Hansen and Nansen (1926) have published maps of the eastern North Atlantic showing the topography of a number of isobaric surfaces relative to the topography of the 2000-decibar surface, and Jacobsen (1929) has published corresponding maps of the greater part of the North Atlantic using the 1000-decibar surface as a basis. Most of the <u>Carnegie</u> stations reach to greater depths than 2000 meters and the results, therefore, can be used for amplifying the maps by Helland-Hansen and Nansen.

Figure 5 shows the topography of the 100-decibar surface relative to the topography of the 2000-decibar surface, based on the anomalies in dynamic meters of the distances between the surfaces. The lines representing the relative topography of the 100-decibar surface are drawn for intervals of 10 dynamic centimeters. The relative flow of the water at a pressure of 100 decibars is parallel to the lines and in the direction which is indicated by the arrows. The flow of the water at a pressure of 2000 decibars is undoubtedly very slow and the lines, therefore, represent very nearly the direction of the absolute currents at the depth where the pressure is 100 decibars, or at a depth of about 100 meters below the surface.

The continuous lines in the figure have been copied, with a few simplifications, from Helland-Hansen and Nansen's map. These lines are based on numerous observations over a period of many years and must, therefore, be expected to represent nearly a true picture of the average topography of the 100-decibar surface in the stated units. The corresponding values at the <u>Carnegie</u> stations are entered in the same units. Some of the <u>Carnegie</u> stations fall within the area which has been examined by Helland-Hansen and Nansen, and the values at these stations are in excellent agreement with their map, except the value 1.30 to the northwest of the Azores. It is very probable, however, that this station is situated in a region where minor whirls occur, such as those which are indicated at other localities in Helland-Hansen and Nansen's map. The broken lines in the figure represent the relative topography of the 100-decibar surface according to the <u>Carnegie</u> data outside the region which previously had been studied. It is seen that these lines can be readily united with Helland-Hansen and Nansen's lines. As we proceed from north to south, along the route of the <u>Carnegie,</u> we recognize the Labrador Current, the Atlantic Drift, the anticyclonic circulation around the Sargasso Sea, and the north equatorial trade-wind drift, which partly continues into the Caribbean Sea.

Figure 6 shows the profile of the isobaric surfaces 0, 100, 200, 300, 400, 500, 700, 1000, and 1500 decibars along Section I, referred to the 2000-decibar surface. It is evident that the currents are strongest in the upper layers because the slopes decrease with increasing depth. It especially should be noted that the 1500-decibar surface is almost level when referred to the 2000-decibar surface, meaning that the currents at 1500 meters vary but little from the currents at 2000 meters.

There are strong reasons for assuming the currents to be very weak at a depth of 2000 meters and we can, therefore, regard the relative slopes in the figure as representing very nearly the actual slopes of the surfaces. The section runs approximately north and south, and a slope to the north represents a current to the east, and vice versa.

To the right in the figure the steep slope between stations 15 and 16 indicates the Gulf Stream. The maximum velocity of this current is reached, according to the slope of the isobaric surfaces, at a level of about 200 meters. Examining the difference between the elevations of the isobaric surface above the 2000-decibar surface, we find:

Isobaric surface	Decibars								
	0	100	200	300	400	500	700	1000	1500
Difference in elevation	Dynamic meters								
(15-16)	.32	.41	.44	.41	.38	.34	.25	.12	.03

The slope of the 200-decibar surface is thus the greatest and remains considerable down to a depth of more than 1000 meters.

Aside from the maximum elevation of the isobaric surfaces at station 15 which must be associated with the presence of whirl, we find the maximum elevation of the 0-decibar surface at station 20, or in latitude about 20°, but the maximum shifts toward the north with increasing depth and at the 200-decibar surface is found at station 18, or latitude 30°. Between stations 18 and 20 we find, thus, a current which is directed toward the east at the surface but toward the west at a depth of 200 meters; below 500 meters it is again directed toward the east.

Disregarding what are probably local conditions between stations 15 and 16, the strongest westerly current is found between stations 20 and 21. This westerly current, in contrast with the Gulf Stream, has the greatest velocity at the surface, but it decreases so rapidly with depth that the current is weak below 500 meters. Examining the differences between the elevations of the isobaric surfaces we find:

Isobaric surface	Decibars								
	0	100	200	300	400	500	700	1000	1500
Difference in elevation	Dynamic meters								
(20-21)	.24	.23	.17	.13	.10	.08	.07	.05	.03

South of station 20, that is, south of latitude 20°, the current is, on the whole, directed toward the west, but irregularities appear to be present.

A corresponding examination of the profiles of the isobaric surface along the parallel of 12° north, Section II, does not produce definite results, which indicates that in this region the east and west currents are much stronger than the north and south currents.

General

Prior to the last cruise of the Carnegie the knowledge of the physical oceanography of the Pacific Ocean was based on results of expeditions which had been undertaken before 1910, the major part of these expeditions having been in the last decades of the nineteenth century. Only the expeditions in the early part of the twentieth century were equipped with accurate thermometers and carried out determinations of the salinity with the precision which now is regarded as necessary. None of the expeditions which have obtained reliable information, however, have operated at great distances from land or in the central part of the ocean. Our knowledge of the conditions of the open ocean is, therefore, primarily based on measurements which do not meet the present requirements as to accuracy. This applies especially to the observed salinities but the temperatures are also inaccurate, as will be shown later when discussing the Carnegie data in detail.

The older observations from the Pacific, however, have given a general view of the thermal and haline characteristics of the waters in the different regions and especially have thrown light over the major features of the stratification of the waters. It has been possible to draw conclusions as to the circulation of the upper strata of the ocean but it has not been possible to disclose the character of the deep-water circulation.

The woeful lack of knowledge concerning the temperature and salinity of the deep water of the Pacific prior to the Carnegie observations is illustrated in figure 7 which shows the location of stations at which observations of temperature and salinity for depths greater than 3000 meters had been made by earlier expeditions (according to Wüst), as compared with those of the Carnegie.

Schott and Schu (1910) have discussed the temperature of the Pacific waters on the basis of the entire material which was available at that time. The isothermal maps which these authors have drawn for the different levels give a good general view of the distribution of temperature, and the major features in their maps are undoubtedly correct.

Conclusions as to the circulation can hardly be drawn on the basis of temperature maps only. Wüst (1929) made use of the observations of density and salinity which had been made on earlier expeditions for the construction of two salinity sections, one representing the salinities in the western part of the Pacific and the other the salinities in the central part. He also constructed temperature sections. The sections through the western Pacific are based, to a considerable extent, on the later observations of the Planet expedition and therefore are more trustworthy than the sections from the central Pacific which are based only on the Challenger's observations, except for the most northern and southern regions. It will be shown later that the temperatures of the Challenger cannot be regarded as having the accuracy which Wüst assumed, and that the salinities which were used for constructing the sections are inaccurate in spite of the great improvements which Wüst introduced by his methods. But, notwithstanding the deficiencies in material, the sections give a correct representation of the more conspicuous features of the stratification of the waters. We shall, therefore, briefly discuss these sections in order to obtain a general view of the conditions in the region which later will be treated more in detail by means of the Carnegie observations. Since it is possible to construct a new section from the Carnegie data, however, we shall use this as representative of the central Pacific and use the section by Wüst for the western Pacific. The Carnegie section for the central Pacific deviates in important details from the corresponding section by Wüst, but the major features in which we now are interested are the same. The four sections with which we are dealing are represented in figures 8 to 11.

The temperature distribution (figures 8 and 10) in the Pacific Ocean is almost symmetrical as to the equator in contrast with the temperature distribution in the Atlantic. In the Pacific we find accumulations of warm water both in the Northern and Southern hemispheres. In the central Pacific the warm water reaches almost to the same latitude in both hemispheres, but in the western Pacific the extension toward the south is greater than the extension toward the north. In both sections the warm water reaches deeper in the Southern Hemisphere and here we have, therefore, the greater accumulation of warm water. In both sections, at about latitude 10° north we find only a very thin layer of warm water, but the highest temperatures for 1000-meter depths are found in this latitude. In both sections the temperature decreases rapidly down to a depth of a few hundred meters. From this depth the decrease continues slowly and regularly to the bottom. The isotherms in the western section show several bends but in the central section they have a smooth course. There we find none of the temperature inversions so characteristic of the corresponding sections from the Atlantic and Indian oceans.

The salinity distribution (figures 9 and 11) does not show such a pronounced symmetry as the temperature distribution. The accumulation of water of high salinity is more conspicuous in the Southern Hemisphere where the vertical extension is greater and where it reaches a greater distance from the equator. This accumulation is more developed in the western than in the central section. The accumulation in each hemisphere is separated from the other by a belt of water of low salinity which follows approximately the parallel of 10°, the same latitude in which the isotherm of 20° approaches the surface.

Below the accumulations of water of high salinity in both hemispheres we find water of very low salinity which appears to penetrate toward the equator from the subarctic and subantarctic regions, representing the intermediate subpolar currents. In the Atlantic this intermediate current is developed only in the Southern Hemisphere but reaches across the equator up to about latitude 20°. In the Pacific the intermediate current appears to be developed almost to the same extent in both hemispheres. In the Northern Hemisphere it penetrates to almost 15° in both the central and western sections; in the Southern Hemisphere it penetrates to almost 20° in the central section and to 30° in the western section. In these sections, however, the salinity curve 34.4 per mille has been used as representing the last traces of the intermediate water, but if 34.5 per mille had been used, we would have found that the intermediate water penetrates to between latitudes 15° and 10° in the Northern Hemisphere and to between latitudes 0° and 10° in the Southern Hemisphere.

Between the last traces of the intermediate water, in the equatorial part of both sections, we find water of

a salinity which is lower than the salinity of both the surface and the deep water.

The deep water which fills the Pacific Basin below a depth of 2000 meters, is, according to these sections, of a very uniform character, with a temperature slightly below 2° and a salinity somewhat above 34.6 per mille.

Defant (1928) has pointed out the advantage of distinguishing between two different horizontal strata in the sea, namely: an upper stratum, the troposphere, within which great variations of temperature and salinity in horizontal and vertical directions are found, and to which the most important currents are confined; and a deeper stratum, the stratosphere, which is characterized by small variations in temperature and salinity both in horizontal and vertical directions, and consequently, by very slow currents. In the Pacific, in accordance with Wüst, we may regard the isothermal surface of 10° as separating the troposphere from the stratosphere. We find then that the troposphere has a maximum vertical extension of about 650 meters in the western Pacific and of less than 500 meters in the central Pacific, and that the stratosphere reaches to the surface of the sea north and south of latitudes about 50° north and south, respectively. The circulation within the troposphere, also in accordance with Wüst, will be called the warm-water circulation, and the circulation within the stratosphere will be called the cold-water circulation.

The Available Data

The observations of the Carnegie are not so numerous that by means of these we can undertake a complete discussion of the physical oceanography of the Pacific. Most of the observations were made north of latitude 20° south. Observations south of this latitude are available only from the South American coast to longitude 120° west. Thus no stations were occupied in the greater part of the South Pacific south of latitude 20° south, and in the North Pacific great regions have not been visited. Considering these wide gaps, it might appear desirable to amplify the data of the Carnegie by means of data from earlier expeditions, in order to make the best possible use of the existing material in the following discussion. None of the earlier observations from the Pacific, however, are of the same quality as to accuracy as the Carnegie data except later observations which have been taken off the coast of California, in the Gulf of Alaska, in the Japanese waters, and the observations of the Planet between New Guinea and Japan. Most of these observations do not reach to as great depths as those at the Carnegie stations. They are well suited for the study of details in the different regions but they contribute little to the knowledge of the major features which enter in the foreground when dealing with the work of the Carnegie. We shall, therefore, make use only of some stations in the Gulf of Alaska which directly form a supplement to the Carnegie stations in this region.

As to the older observations, it has already been emphasized that these are less accurate than the later ones. In order to illustrate this the vertical temperature distribution at three Challenger stations and three Carnegie stations (which were taken in approximately the same localties) is represented in figure 12. It is seen that the general features of the temperature distribution agree well, but the results differ considerably in details. Comparing the stations Challenger 254 and

Carnegie 143 we find that the Carnegie observations show a decrease of the temperature at all levels, whereas the Challenger observations show three inversions. The two lower inversions, however, fall between levels at which the Carnegie observed, and at the latter levels agreement exists between the Challenger and Carnegie temperatures. It is possible, therefore, that the inversions existed when the Carnegie station was occupied but escaped detection because the observations were made at too great intervals. A comparison between stations Challenger 262 and Carnegie 139 shows that this conception can hardly be upheld. The Carnegie station again shows a decrease of temperature at all levels, whereas the Challenger station indicates a succession of intervals with small decrease or inversions. At this station the intervals of the Carnegie observations are again much greater than the intervals of the Challenger observations, but a Carnegie observation was made at the level at which a Challenger observation indicates an intermediate minimum of 1.°56. The Carnegie observation shows no such minimum but the value lies practically on the straight line joining the two adjacent observations. The irregularities of the Challenger values which occur above a level of 500 meters are actually of the same order of magnitude as the irregularities at a greater depth but they are less conspicuous because of the rapid change of temperature with depth. The observations at the two stations Challenger 280 and Carnegie 87 agree, on the whole, very well but below a level of 800 meters the Challenger temperatures appear to be as much as 0.°3 too high.

These three examples show that the reality of the small inversions which were observed at great depths on the Challenger must be doubted and the same also applies to the intervals with small temperature gradients in the upper layers. Such irregularities are never found at the Carnegie stations, as is evident from the temperture curves of the following figures reproduced in I-B: 94, 100, 106, 112, 118, 127, 133, 142, 148, 154, 160, 166, 172, 178, 187, and 196.

It is true, as already mentioned, that the Carnegie observations have been made at greater intervals than the Challenger observations, but if inversions at great depths were as frequent as indicated by the Challenger data, they would undoubtedly have been observed at some stations and have changed the smooth course of the curve. Considering this circumstance we cannot agree with Wüst in accepting the small inversions as representing actual conditions. The Carnegie observations strongly indicate that, although the Challenger data give a true representation of the major features of the temperature distribution, the details cannot be relied on. This result is in agreement with the conception of the officers of the Challenger because, in the report on the deep-sea temperature observations, smooth curves have been drawn by means of the observed data and the values scaled from curves have been given beside the observed values. The smooth curves agree, on the whole, with the Carnegie curves, and the results from the upper layers could be used for amplification of the Carnegie data, but the deep-sea temperatures from the two expeditions are not comparable.

With the exception of the later expeditions referred to previously, the observations of temperature by the other expeditions which have cruised in the Pacific have not been made by means of more superior methods. It is not advisable, therefore, to combine the results of

these earlier expeditions with the Carnegie results. The same applies, to a still greater extent, to the salinities. Numerous observations of the salinity have been made by the Challenger but, as stated before, these have not the accuracy which permits combination with modern data. The following discussion of the physical oceanography of the Pacific will be based, therefore, principally on the Carnegie data alone.

Temperature and Salinity

Horizontal Distribution

The values of temperature and salinity, scaled from graphs for each station, have been entered in figures 210-233; I-B, and isotherms and isohalines have been drawn in order to bring out the characteristic features. It must be emphasized, however, that at the higher levels these lines have no well-defined physical significance. They do not represent the values at a given moment nor the mean annual values because the observations have been made in different seasons in the different regions.

In the upper layers great deviations from the average annual conditions must be expected because of seasonal variations in heating and cooling. In the courses of the currents and because of irregular changes, but at greater depths, such variations are probably small and here the lines can be expected to represent the average conditions, although they are based on a small number of observations.

By means of earlier observations, Schott and Schu (1910) have prepared charts showing the horizontal distribution of temperature at different levels down to a depth of 4000 meters, and Schott (1928) has published a chart showing the distribution of the salinity at the surface. In the following we shall undertake some comparisons between these charts and those derived from the Carnegie data.

Surface.--At the surface (figure 210; I-B) the temperature in the Northern Hemisphere decreases regularly from the equator toward the north in the western part of the Pacific. In the eastern part of both hemispheres the isotherms are bent toward the equator but more so in the Southern Hemisphere, where a region of low temperature can be followed along the equator from the Peruvian coast toward longitude 150° west. In the western part of the ocean a corresponding bend of the isotherms toward the equator is found to the northeast of Japan, going from Bering Sea down to latitude 40° north.

The chart by Schott and Schu shows the mean annual isotherms and, therefore, it cannot be expected that the Carnegie data will agree with the chart values because of the annual variation of the surface temperature. The Carnegie observations were made in summer in both hemispheres, for which reason they must be higher as a rule than the means for the year. Comparing the Carnegie data with the corresponding values which can be read off the Schott-Schu chart, we find that the Carnegie temperatures generally are higher. The most striking exception is in the vicinity of the Galapagos Islands, where, at stations 41, 42, 43, 44, and 45, the average deviation from the chart values is -2.°2.

It is not possible to reduce the Carnegie observations to the mean of the year because sufficient data as to the annual variation are lacking. The Marine Imperial Institute at Kobe, Japan has published mean monthly

isotherms for the greater part of the North Pacific, but the charts do not cover the entire area in question. For the equatorial regions Puls (1895) has published monthly isotherms, but these do not quite agree with the above-mentioned in the areas where the two representations overlap. In order to eliminate the effect of changes in the currents on the temperature distribution (Helland-Hansen, 1930) it would be necessary, furthermore, to take the salinity variations into account, but isohalines for each month are not available. The foundation for a reduction of the observed temperatures to the mean of the year is, thus, insufficient, but we can draw attention to the character of the differences between the Carnegie values (C) and the mean annual temperatures as represented by Schott and Schu (SS) and by Japanese charts (Jap). We also shall examine the differences between the Carnegie data and the corresponding mean monthly values as shown in Japanese charts and in those by Puls.

Forming mean values we find for the North Pacific, from stations 98 to 140: $C - SS = +1.°9$,
$$C - Jap \text{ (year)} = +2.°0,$$
$$C - Jap \text{ (month)} = +0.°7;$$
for the equatorial regions, from stations 35 to 47:
$$C - SS = -1.°1,$$
$$C - Puls = -0.°1;$$
from stations 70 to 74, 93 to 109, 138, 139, and 149 to 162: $C - SS = +1.°5$,
$$C - Puls = +0.°5.$$

The differences between the Carnegie observations and the values from the Schott-Schu chart are shown in table 7, where they have been arranged in groups according to the latitude, and where the months in which the observations were taken, are shown. The table also contains the differences in salinity according to the Carnegie observations and Schott's chart to which we shall return presently. In this place it will be pointed out that the Carnegie observations give the relatively highest temperatures in the middle part of the North Pacific in the months of September and October and the relatively lowest values, aside from the conditions in and near the Gulf of Panama, in the equatorial region in April and May.

Table 7. Differences in temperature and salinity between the Carnegie observations (C) and the values from charts by Schott and Schu (SS) and Schott (S)

Stations	Latitudes	Months 1928-1929	Temperature C - SS	Salinity C - S
	° °		°C	°/oo
35- 48	7 N-20 S	Oct., Nov.	- 1.0	-0.06
49- 68	20 S	Nov., Dec., Jan.	+1.5	-0.34
69- 93	10 S-20 S	Jan., Feb., Mar.	+2.1	-0.18
94-108	20 S-20 N	Apr., May	+0.3	-0.23
109-129	20 N	May, June, July	+2.0	-0.20
130-149	20 N	Sep., Oct.	+3.6	+0.01
150-162	20 N-20 S	Oct., Nov.	+1.5	-0.19

These features, and the fact that the differences are reduced when comparing with monthly charts, indicate that the discrepancies between the Carnegie observations and the annual values according to Schott and Schu principally are because of the annual variation of the surface temperature, but part of the variation is probably connected with accidental changes in the currents.

The surface salinity (fig. 222; I-B) shows a less symmetrical distribution than the temperature. Two maxima of salinity are found, one in the Southern, and one in the Northern Hemisphere. The former has its center in the eastern part of the ocean in approximately latitude 20° south and longitude 120° west, whereas the latter has its center in the western part of the ocean in approximately latitude 25° north and longitude 175° east. These two areas of high salinity are separated by a narrow belt of low salinity in about latitude 10° north, the lowest salinities occurring in the eastern part of the ocean. Near Central America the salinities are very low, probably because of local conditions. To the north and the south of the areas of high salinity, the surface salinity decreases toward the poles. This decrease appears to be greater in the Northern Hemisphere, where salinities approaching 32.5 per mille are found in the inner part of the Gulf of Alaska and to the northeast of Japan.

The chart of the surface salinity by Schott represents approximately mean annual isohalines, but in several regions the observations on which the mean annual values are based, are distributed unevenly over the year and the actual annual values may, therefore, deviate somewhat from the values of the chart.

The Carnegie data are smaller than the values by Schott on the whole. Negative differences are found in eighty-seven of one hundred and twenty-eight cases and positive differences in nineteen cases only. As a rule, the differences are small and equal to or smaller than 0.3 per mille in ninety-one instances. The mean of all is -0.17 per mille.

Within the equatorial region no relation exists between the simultaneous deviation from the mean values of temperature and salinity. This becomes evident when plotting the corresponding values in a temperature-salinity diagram, and is also evident from table 7, which contains the corresponding average values for certain regions. Outside the equatorial regions, on the other hand, we find a distinct relation between the corresponding deviations: on the average a high temperature corresponds to a high salinity, and vice versa. This is seen when plotting the corresponding deviations and is also evident from table 7 where, within the three areas outside the equatorial regions, we find for values of t, 1°5, 2°0, and 3°6 and the values of $\underline{S}$ are -0.34, -0.20, and +0.01 per mille, respectively.

An increase of 1° in the temperature deviation thus appears to correspond to an increase of 0.15 per mille in the salinity deviation. This increase corresponds to the normal temperature-salinity relation which is found in the Pacific. The relation found between the deviations from the chart values, thus can be interpreted to indicate either that the annual variations in temperature and salinity are parallel to one another, or that part of the temperature deviations have nothing to do with the annual variation of temperature but are caused by changes in the currents and, therefore, are accompanied by parallel variations in salinity. At present it is impossible to decide which of these factors is of the greater importance.

One hundred-meter level.--At this level the temperature distribution (fig. 211; I-B) is already materially changed and the difference between the conditions in the eastern and western parts of the ocean is much more pronounced. Here we find a temperature of 12° off Callao, which increases as one proceeds toward the west,

reaching 20° at the meridian of 100° west, whereas at the surface the corresponding temperatures are 18° and 23°. Off San Francisco we find a temperature of 9° increasing to 14° at the meridian of 140° west, whereas the corresponding surface values are 13° and 16°. The most conspicuous feature, however, is that north of the equator in about latitude 10° north and longitude 140° west a temperature of 11° is found where the surface value is about 24°.

Comparing the Carnegie observations at 100 meters with the values by Schott and Schu, we find deviations of a less systematic character than at the surface. Within wide areas the deviations are small and of changing sign, the mean of all being 0°37. Deviations greater than 5° are found off Japan, to the south of Bering Sea, and to the north of the equator between the parallels of 5° and 15° north, in the region of the Equatorial Countercurrent.

The Schott-Schu chart shows a belt of temperatures below 20° stretching across the ocean in about latitude 10° north and separating the warm water masses of the two hemispheres. In the figure this belt of low temperatures is shown in the eastern part of the ocean only, but it must be admitted that in the western part the distances between the stations are so great that the feature may have escaped observation.

The seasonal variation of temperature due to the influence of heating and cooling is probably very small at the 100-meter level (Helland-Hansen, 1930). The difference, therefore, cannot be ascribed to such seasonal variations, but must be related to changes in the currents. These changes may be of an accidental or periodic character and influence both temperature and salinity distribution. We have no means of examining corresponding temperature and salinity deviation, but the fact that the greatest differences in temperature occur in regions where strong and varying currents prevail, indicates that the discrepancies are owing to displacement of these currents.

The distribution of the salinity at the 100-meter level (fig. 223; I-B) shows the same features as at the surface, but the difference between the western and eastern part of the ocean is more pronounced. Very low salinities are found off the Peruvian and Californian coasts. The minimum north of the equator is less pronounced.

Two hundred-meter level.--The temperature distribution (fig. 212; I-B) shows a new and interesting feature. At this level the belt of low temperatures to the north of the equator can be followed across the ocean as far as the observations are extended, and a similar belt appears to be present directly to the south of the equator, whereas higher temperatures prevail at the equator.

The typical region of low temperature, which at higher levels could be followed from the coast of Peru toward the west along the equator, has now moved to the south and is found entirely in the Southern Hemisphere.

In the Schott-Schu chart only one belt of low temperatures to the north of the equator is seen, the second belt to the south of the equator is not present. It is possible that the existence of the two belts is connected with the special development of the currents at the time when the Carnegie observations were made, but even if this is the case, the feature is characteristic of the conditions in the central Pacific.

The average discrepancy between the Carnegie observations and the corresponding values according to

Schott and Schu is of the same order as at the 100-meter level and the greatest deviations are found, as previously, where strong currents prevail.

The character of the salinity distribution (fig. 224; I-B) is not much changed except that the difference between the conditions in the northern and southern parts of the ocean is more prominent. In the Northern Hemisphere salinities above 35 per mille occur only within a narrow strip where the temperature exceeds 20°, whereas in the Southern Hemisphere salinities above 35 per mille are found over a wide area stretching toward the east into regions where the temperature is considerably lower than 20°. Here isolated areas with a salinity above 36 per mille are present. Off the coast of Chile we find a tongue of low salinity in the region where a corresponding tongue of low temperature is present.

Three hundred-meter level.--At this level we find, principally, the same distribution of temperature (fig. 213; I-B) as at 200 meters. The two belts of low temperatures on both sides of the equator and the high temperatures between them appear more clearly, and the tongue of low temperatures off the Peruvian coast has moved somewhat farther south. The warm-water accumulations in both hemispheres are more clearly separated.

The distribution of salinity (fig. 225; I-B) is more uniform than at higher levels. In the Northern Hemisphere the accumulation of water of high salinity is seen in the eastern part only, but the values do not exceed 34.7 per mille. In the Southern Hemisphere the accumulation of very salty water is still fairly well developed with values above 35 per mille in a wide region.

In both hemispheres tongues of low salinity penetrate toward the equator in the western part of the ocean. In the Northern Hemisphere the tongue nearly coincides with a corresponding tongue of low temperatures, but in the Southern, the low salinities are found considerably more to the south than the low temperatures.

Four hundred-meter level.--The temperature distribution (fig. 214; I-B) is principally the same as at 300 meters, but the differences between the values in different parts of the ocean are smaller. At this level a connection is clearly seen between the two equatorial belts of low temperature and the tongue of low temperature in the western part of the ocean. The discrepancies between the Carnegie data and the Schott-Schu chart are of the same character as previously.

The salinity distribution (fig. 226; I-B) also shows the same features as at 300 meters, but now only traces of the accumulation of water of high salinity are present, and the tongues of water of low salinity on the western side of the ocean are still more pronounced.

Five hundred-meter level.--Here we find again a similar distribution of temperature (fig. 215; I-B), but the high temperatures at the equator appear more clearly and to the north of the equator we find alternating high and low temperatures where, at higher levels, there was a belt of low temperatures only. The highest temperatures are found in the Northern Hemisphere where there are values above 10° in the eastern part of the ocean.

The distribution of salinity (fig. 227; I-B), on the other hand, is much changed as compared with the distribution at higher levels. At 500 meters we find no trace of accumulations of water of high salinity in either hemisphere, but the maximum values are found along the equator where, however, they remain lower than 34.65 per mille. The tongues of low salinity on the

western side of the ocean are still present, and in the Northern Hemisphere salinities lower than 34.1 per mille appear to be characteristic of the entire central part of the North Pacific.

Seven hundred-meter level.--Here the temperature contrasts (fig. 216; I-B) are still smaller, but the character of distribution is not much changed. Traces of the warm-water accumulations are still seen in both hemispheres, and the characteristic tongues of low temperatures at the western side of the ocean can be followed.

At this level the highest salinities (fig. 228; I-B) are also found at the equator, but the values nowhere exceed 34.60 per mille. In the Southern Hemisphere a tongue of low salinity is still present at the western side of the ocean, but in the Northern Hemisphere the corresponding tongue has disappeared and the lowest values are found in the central part of the North Pacific.

One thousand-meter level.--At this level a considerable change in the character of the temperature distribution (fig. 217; I-B) has taken place. In the equatorial region we find alternating strips of low and high temperatures. In the Northern Hemisphere the temperature decreases fairly regularly toward the north, but now there are high temperatures off the coast of California, where at higher levels low temperatures prevail. In the Southern Hemisphere the tongue of low temperature in the western part of the ocean is still present, but it has been displaced somewhat to the south.

At this and lower levels the charts by Schott and Schu show higher temperatures, on the whole, than do the Carnegie observations. Detailed comparison is of minor interest because the data on which the charts are based are less accurate than the Carnegie observations. The distribution of the salinity (fig. 229; I-B) is very similar to the distribution at 700 meters, but the contrasts are smaller and the maximum values in the vicinity of the equator are also smaller.

Fifteen hundred-meter level.--Here the temperature distribution (fig. 218; I-B) in the Northern Hemisphere has the same character as at 1000 meters, but in the Southern Hemisphere the characteristic tongue of low temperatures has disappeared, and instead, a tongue of high temperature stretches toward the south in longitude 95° west. As to the distribution of the salinity (fig. 230; I-B), the maximum values are still found in the equatorial region and are now slightly above 34.6 per mille and the low values in the central part of the North Pacific have almost disappeared.

Two thousand-meter level.--The temperature distribution here (fig. 219; I-B) is similar to the distribution at 1500 meters, but the contrasts are smaller. The highest temperatures, above 2°.3, are found near the equator, whereas the lowest values, 1°.8, are directly to the south of Bering Sea. The salinity (fig. 231; I-B) is higher than at 1500 meters. Values below 34.6 per mille are found off the coast of Chile, in a limited area near the Samoan Islands, and in the greater part of the North Pacific.

Twenty-five hundred-meter level.--At this level the temperature distribution (fig. 220; I-B) shows new and interesting features. Temperatures above 1°.9 are found in the vicinity of the equator and in the southern part of the South Pacific, whereas in the northern part of the South Pacific temperatures slightly below 1°.9 appear to prevail. In the North Pacific an area with temperatures below 1°.7 covers the northern part, but in the Gulf of

Alaska, to the south of Bering Sea, and off the coast of Japan, slightly higher temperatures are present. The distribution of the salinity (fig. 232; I-B) at this level is so uniform that no isohalines can be drawn, but a general decrease of the salinity from south to north appears to be characteristic at this level. Values approaching or slightly surpassing 34.7 per mille are found at the most southern stations, whereas in the North Pacific the salinity is only slightly above 34.6 per mille.

Three-thousand-meter level.--The temperature distribution (fig. 221; I-B) here is very uniform. Near Central America values above 2.°0 are observed, but elsewhere the temperature varies between 1.°85 in the basin off the Peruvian coast to 1.°55 in the central part of the North Pacific. The lowest values again appear to be present in the northern part of the North Pacific, whereas high values prevail in the equatorial region. The material is very scanty, but the variations are sufficiently systematic to give significance to the isotherms which have been drawn. At this level the salinity (fig. 233; I-B) appears to decrease from south to north, varying from 34.68 per mille in latitude 40° south to 34.63 per mille in latitude 40° north. In the southern part the values are approximately the same as at 2500 meters, but in the northern part they are slightly higher.

Concerning the salinities it must be added that these, according to the discussion given on page 72, appear to be about 0.03 per mille too low. This systematic error is of no importance in the upper levels but at great depth it exerts an influence on the course of the isohalines.

The warm water of the Pacific.--We have seen that at the 700-meter level the distribution of both temperature and salinity is quite different from the distribution at higher levels. Therefore, we conclude that the warm water circulation in no locality reaches as far down as the 700-meter level. At the 500-meter level traces of this circulation were seen in the temperature distribution only, and considering that the temperature at 500 meters is lower than 10° and that we have previously regarded the isothermal surface of 10° as representing the lower boundary of the troposphere, we conclude that the warm-water circulation practically has disappeared below the 500-meter level.

Intermediate water of the Pacific.--The intermediate water of low salinity is first clearly seen at the 400-meter level in the eastern part of the North Pacific where the low salinities off the Gulf of Alaska continue toward latitude 25° and bend toward the west somewhat to the north of this latitude. The isotherms show a corresponding but less pronounced bend toward the west. In the Southern Hemisphere the corresponding intermediate current appears to be present in the region to the west of South America. At the 500-meter level the intermediate current evidently reaches farther west in the Northern Hemisphere as indicated by the course of the isohalines and also by the characteristic bend of the isotherms. At the 700-meter level the intermediate current is less strongly developed in the eastern part of the North Pacific where the salinities now are higher than at the 500-meter level. The lowest salinities are now found farther west. In the Southern Hemisphere the intermediate current can be traced up to about 15°. At the 1000-meter level we are evidently below the intermediate current because the salinities are higher here than at 700 meters both north of latitude 20° north and

south of latitude 20° south. The intermediate current thus appears to be most strongly developed between depths of 400 and 700 meters in the Northern Hemisphere, and to lie at a higher level in the eastern part of the ocean. In the Southern Hemisphere it appears from the horizontal charts to be most prominent at a level of 700 meters. The last traces of the intermediate currents do not reach to lower latitudes than about 15° and 10°. Between these latitudes we find water of a uniform salinity which is higher than the salinity of the intermediate currents but lower than the salinity of the deep water.

Deep water of the Pacific.--The deep water of the Pacific is very uniform; the temperature decreases slowly with increasing depth and the salinity increases slowly. In a horizontal direction we find a decrease of salinity from south to north and maximum temperatures at the equator, but the total range of temperature is less than 0.°2, except the local conditions near Central America. The uniform character of the deep water is illustrated by the following table, which shows average values of temperature and salinity at the depths 2000, 2500, and 3000 meters within stated intervals of latitude. It is seen that the range of the average temperatures decreases slowly with depth whereas the range of the average salinities remains equal to 0.04 per mille, and the absolute values decrease from south to north at each level. But as a result from a general discussion of the salinity values, it seems probable that salinities as tabulated and graphed should be increased by 0.03 per mille. The discussion on which this conclusion is based is presented in Physical Oceanography I-B of the "Scientific results of cruise VII of the Carnegie."

Vertical Distribution

When discussing the horizontal distribution of temperature and salinity we considered the most prominent features of the vertical distribution and especially emphasized that the waters of the Pacific show a typical stratification both as to temperature and salinity. Turning to a more detailed discussion of the vertical distribution, we shall base this on the representations in the vertical sections and shall also make use of the curves which show the observed data at each station. As to the construction of the sections we refer to the explanation of the graphs.

Section III.--Section III embraces stations 37 to 40 and 60 to 72, begins near the Gulf of Panama, follows the coast of South America down to latitude 17° south, and continues south-southwest to latitude 40° south. Two stations in the Gulf of Panama, stations 35 and 36, were not included when constructing the section.

The topmost layer of the troposphere has been called by Defant the zone of agitation (Størungszone), representing the layer within which convection currents can mix the water thoroughly. It is perhaps better to use the term convection layer because this term better expresses the character of this uppermost stratum.

Off Central America the convection layer is very thin. At station 35 it does not reach to 27 meters and has a salinity of 29.8 per mille and a temperature of about 27.°5. At stations 36, 37, 38, and 39 the thickness of the layer is between 20 and 30 meters. The salinity increases up to 33 per mille at station 39. The temperature is about 27° at the previous three stations and

about 25° at station 39. At station 40 the convection layer has a thickness of less than 23 meters, the salinity is slightly above 34 per mille but the temperature is only 20°.4. At the next stations, 69 to 72, we also find a very thick convection layer which never reaches to a depth of 40 meters. The surface salinity is higher here, being above 35 per mille, but the temperature is low especially at station 71 which has been taken at a short distance from the coast. Proceeding toward the south along the section we find that the convection layer remains thin at all stations, but the transition from the convection layer to the deeper layers becomes more and more gradual. This is especially evident when we take the density into account. At station 71 we have, for instance, an increase in σ_t from 24.05 at 19 meters to 25.36 at 40 meters, whereas at station 60, σ_t increases only from 25.32 to 25.51 between 24 and 47 meters.

The heating by radiation and contact with the atmosphere and the influence of evaporation and precipitation are primarily responsible for the temperature and the salinity of the convection layer, but transport of water from deeper layers may also be of importance. In this place we shall especially emphasize that the low salinity in the region of Central America must be ascribed to the influence of precipitation because we have no inflow of water of low salinity to this region, and because no large rivers carry considerable quantities of fresh water into the sea. The high salinities off the Peruvian coast, on the other hand, must be attributed to the effect of evaporation because this water is transported toward the coast from the south where the salinity is lower, or to the effect of "upwelling" which brings water of higher salinity to the surface.

Below the convection layer we find a more or less rapid decrease of the temperature with increase with depth. The decrease is especially very rapid at the stations which have been taken at a short distance from the coast of Peru, but is more gradual at the southern stations. The isotherm of 15° sinks from stations 60 to 67 and rises between stations 67 and 70. The isotherm of 10° also sinks between stations 60 and 67 but up to station 71 this isotherm continues sinking and runs horizontally north of this station. The isotherm of 5°, on the

other hand, runs almost horizontally up to station 67 and sinks from this station as it proceeds to the north. The rise of the isotherm of 15° between stations 67 and 70 indicates an accumulation of cold water in the upper layer; but this accumulation does not reach below the level of the 10° isotherm and is thus a phenomenon of the troposphere.

The distribution of the salinity is much more complicated except in the northern part of the section where the salinity decreases regularly down to a depth of 1000 meters. South of station 72 we find many irregularities in the vertical variation of the salinity at the different stations, but in the section two major features are seen. The salinity of the water above a depth of about 200 meters increases, on the whole, from south to north. As already mentioned, this increase must be attributed to the influence of evaporation because it is more rapid at the surface. The tongue of low salinity, which extends from station 68 to station 70 at a depth of 150 to 200 meters, is probably associated with an upwelling movement in the upper layers. Below a level of 400 meters we find a layer of minimum salinity representing the intermediate antarctic current. The axis of the lowest values sinks from a little less than 500 meters at station 60 to about 700 meters at station 69, and in the same distance the salinity increases from 34.2 to 34.5 per mille. The axis practically follows the isotherm of 6°. To the north of station 69 water of salinity between 34.5 and 34.6 per mille is found between depths of about 500 and 1500 meters.

The deep water below a level of 2000 meters has a very uniform character. The salinity increases slightly toward the bottom.

In the Peruvian Basin the temperature appears to have a constant value of 1°.83 below a level of 2700 meters, but at the southern stations, 60 to 66, the temperature decreases with increasing depth. The lowest temperature was found at station 60 where 1°.23 was observed at a depth of 3617 meters, 400 meters above the bottom.

Section IV.--Section IV, comprising stations 45 to 51, also represents a section approximately north and south in the same general region but at a greater distance from the coast. Here the convection layer has a considerably

Table 8. Deep-sea temperatures (t) and salinities (S) in the Pacific arranged according to latitude

Area		Number of Stations	Depth in meters					
Latitude	Longitude		2000		2500		3000	
			t, °C	S, °/oo	t, °C	S, °/oo	t, °C	S, °/oo
53 N 40 N	153 E 120 W	12	1.91 (12)	34.58 (12)	1.71 (11)	34.61 (11)	1.62 (7)	34.63 (7)
40 N 20 N	140 E 120 W	29	2.04 (29)	34.59 (29)	1.74 (27)	34.62 (27)	1.60 (19)	34.63 (19)
20 N 0	140 E 130 W	18	2.19 (16)	34.62 (16)	1.84 (15)	34.63 (15)	1.69 (12)	34.64 (12)
0 20 S	180 70 W	44	2.20 (42)	34.62 (42)	1.89 (41)	34.64 (41)	1.77 (24)	34.66 (24)
20 S 41 S	120 W 70 W	20	2.17 (19)	34.62 (19)	1.90 (18)	34.65 (18)	1.76 (12)	34.67 (12)
Maximum - minimum			0.29	0.04	0.19	0.04	0.17	0.04

Numbers in parentheses indicate number of stations included. Salinities probably 0.03 o/oo too low.

greater thickness, especially in the central part of the section, where at station 48 it reaches to almost 80 meters, and at station 45 it exceeds 60 meters, but at station 51 it reaches to less than 25 meters. The zone of rapid transition sinks as one proceeds to the south along the section. The distribution of temperature does not show any other conspicuous features.

The salinity has high values at the surface, surpassing 36.00 per mille between stations 47 and 50. A tongue of salinity above 36.00 per mille stretches past station 47 to the north, which indicates a transport of water of high salinity at a depth of about 100 meters. In the southern part of the section the intermediate antarctic current is recognized by the tongue of low salinity at a level of about 700 meters. The axis of the lowest values apparently rises as it proceeds toward the north and reaches a level of about 600 meters to the north of station 48. The axis again nearly coincides with the isotherm of 6° and this isotherm shows a corresponding but smaller rise. The deep water has the same uniform character as in the preceding section.

Section X.--Section X (stations 51, 52, and 55 to 60) runs from southeast to northwest from station 51 to 60. The convection layer is thin at all stations, and exceeds 30 meters only at stations 55, 56, and 57. The isotherms sink toward the northwest in the upper layers, which indicates that we approach the warm-water accumulation. Below 800 meters they run horizontally.

The salinities are also highest to the northwest, where values above 35.5 per mille are found, and where the course of the isohalines indicates that water of high salinity is spreading toward the southeast. In the most southeastern part of the section we find very low surface salinities, probably characteristic of the easterly current in this region. The decrease of the surface salinity in a horizontal direction is especially rapid in the region of station 57, and here the northern limit of the easterly current may be sought. The belt of salinity below 34.4 per mille at a depth of 600 to 800 meters represents the intermediate antarctic current. The axis of the lowest values is found at approximately 800 meters at station 51 and rises to about 650 meters at station 60. At stations 51 to 57 the axis follows the isotherm of 5° but at stations 58 to 60 it follows the isotherm of 5.°5. The isotherms in these layers, however, also show a rise toward the southeast which corresponds to the rise of the axis. The deep water has a temperature which decreases regularly with increasing depth, but the salinity of the deep water shows a more irregular distribution. At stations 58 to 60 salinities above 34.7 per mille have been observed, being the highest values which were found below the 2000-meter level.

Section XI.--This section (stations 71 to 93) runs practically east and west, and follows approximately the parallel of 18° from the Peruvian coast to the Samoan Islands.

In the eastern part of the section, off the South American coast, the convection layer is very thin, only about 20 meters as a rule, but the thickness increases toward the west and exceeds 50 meters at several stations.

In the western part of the section, which is taken in the central region of the South Pacific Ocean, we find an accumulation of warm water which reaches to a depth of more than 400 meters, if we regard the isotherm of 10° as representing the lower limit of the warm water. High temperatures, above 25°, are found to the west of station 78 only, and the isotherms of 20° and 15°, which are found at a considerable depth in the central part of the ocean, rise almost to the surface as they approach the coast. The rise of these isotherms indicates an accumulation of cold water at the coast, but this accumulation is characteristic of the upper layers only because the isotherms below 300 meters are horizontal or sinking as they near the coast. Thus all isotherms below the isotherm of 7° are found at a lower level off the Peruvian coast than in mid-ocean.

The salinity distribution in the troposphere is characterized by high values to the west of station 77. At most stations a salinity maximum is found at a short distance below the surface and this must be attributed either to the influence of seasonal variations or to the existence of subsurface currents which transport water of high salinities from regions south of the section. The isohalines rise as they approach the South American coast, which shows that the cold water at the coast has a low salinity. The salinity decreases very rapidly with increasing depth between 200 and 300 meters, and at a depth of 600 or 700 meters we find in the whole section low salinities representing the northern part of the intermediate antarctic current. The axis of the layer of low salinity sinks slightly toward the coast and runs on an average, at a level of about 650 meters in the eastern part. The temperature along the axis is nearly 5.°5 over the whole distance, and the sinking of the axis nearly corresponds to the sinking of the isotherms. The bottom water is very uniform, the isotherms running nearly horizontally, but the salinity appears to be higher at the same level near the South American coast than in mid-ocean.

Section XII.--Section XII (stations 40 to 45) also runs approximately east and west and follows nearly the parallel of 2° from the South American coast to longitude 105°. The section thus represents conditions in the eastern part of the Pacific very near the equator.

The convection layer is very thin at the coast but increases systematically toward the west, and has a thickness of nearly 60 meters at station 45. The temperature in the upper layer is very low, remaining below 23° at all stations and being lower than 20° at stations 42 and 43. These stations were within the area of low temperature which, according to the chart showing the temperature distribution at the surface, stretches toward the west from the South American coast. The temperature decreases rapidly directly below the convection layer, but this rapid decrease takes place in a short distance only.

The salinities on the whole are low, especially at a short distance from the coast, and show a maximum at a level of approximately 100 meters, perhaps representing a transport of water from the southwest at this level. A layer of low salinity is also found in this section, and it lies deeper than in the previously discussed sections. The minimum is not very pronounced, the lowest values being higher than 34.5 per mille. The axis of the lowest values is found at approximately 900 meters where the temperature is about 5°. The isotherm of 5° sinks slightly toward the coast but the salinity minimum is not so well defined that the axis of this minimum can be traced with any certainty, for which reason it cannot be seen whether or not this axis deviates from the horizontal direction. The deep water is again very uniform with a temperature which decreases slowly with increasing depth and a salinity which increases slowly.

Section V.--Section V, comprising stations 130 to 134 and 148 to 162, runs from San Francisco toward the southwest to Samoa. It passes through regions of different character and we shall, therefore, first discuss the part of the section which lies between latitudes 20° north and 20° south, namely, stations 149 to 162.

At the most northern (station 149) of these stations the convection layer has a thickness of about 50 meters, but at station 151 in latitude 12° 40' north the thickness is not much greater than 10 meters. Proceeding toward the south the thickness again increases more or less regularly and at station 160 has a value of about 100 meters. The highest temperatures at the surface are found at stations 150 and 158 to 162. The temperature decreases rapidly with increasing depth below the convection layer, and this decrease is especially rapid at stations 151 and 152, where all isotherms showing a temperature of 10° and more are curved toward the surface. At stations 151 and 152 we thus find an accumulation of water of relatively low temperature, but this accumulation only reaches a depth of about 400 meters. Below this depth the highest temperatures are found at stations 151 and 152 down to a depth of 1000 meters, but at still greater depths the temperature maximum wanders toward the south and at a level of 2500 meters is found below station 155 in latitude 4° 51' north. It should be noted especially that the isotherm of 5° rises from its lowest position more rapidly to the north than to the south. The temperature distribution thus shows an accumulation of cold water at stations 151 and 152 down to a depth of less than 400 meters, and below this depth an accumulation of warm water is shown. These accumulations indicate an ascending vertical movement above a level of 400 meters and a descending movement below this level. The latter appears to be more pronounced to the north than to the south.

The salinity distribution in this section shows a number of remarkable features. At stations 151 and 152 the surface salinity is below 34.00 per mille and these very low values probably must be attributed to the effect of precipitation. Both to the north and to the south of these two stations the surface salinities are considerably higher, but the maximum values are found about 100 meters below the surface. The subsurface maximum is well developed especially to the south of the equator where the distribution indicates that at a level of about 100 meters a considerable transport of water of high salinity takes place toward the north. At station 150 to the north of the equator, we find a slight indication of a similar transport toward the south. The very low surface salinities which were observed between stations 159 and 162 are difficult to explain. It is possible that the flow of water of high salinity at a level of 100 meters is intermittent, and that water of low salinity may reach the surface in some localities and spread out. It is also possible that the water of low salinity, which is found to the north of the equator, occasionally spreads toward the south.

Below the layers of high salinity we find a region of low salinities between 500 and 1500 meters. To the north of station 151 water of low salinity, representing the subarctic current, penetrates toward the south. As will be shown later, it is probable that the major part of this water flows toward the east in the region with which we are dealing, but from the section it is evident that part of the water continues toward the south. This current divides into two branches, one ascending above a

level of about 400 meters and the other descending below this level. The vertical distribution of the salinity thus confirms the conclusions which were drawn from the course of the isotherms as to the vertical movement. In the most southern part of the section water of a salinity below 34.5 per mille penetrates toward the north at a level of about 750 meters where the temperature is 5°5. Between stations 151 and 158 we find water of a uniform salinity a little below or a little above 34.5 per mille.

The deep water is again of a uniform character. The temperature decreases to values below 1°5 and at station 149 it again increases slightly when approaching the bottom. Later we shall discuss the temperature at the greatest depths. The salinity of the deep water is practically the same within the whole section.

Turning next to the northern part of the section from San Francisco to station 149 we find in this region a thin convection layer, which at all stations has a vertical extension of less than 50 meters. The lowest surface temperatures are found off the coast and here the isotherms rise rapidly when approaching the coast. This rise, however, is found only down to a depth of 400 meters, which indicates that an accumulation of cold water is confined to the upper layers. The salinities of the upper layers are very low in the vicinity of the coast where a rapid increase takes place at about 200 meters. In the section it appears as if the low salinities, which at greater distances from the coast are found at a depth of 400 meters, form a direct continuation of the low values near the surface at the coast. It will be shown later on, however, that this cannot be the case and that the water of low salinity at the coast, and the intermediate water at 400 meters belong to distinctly different currents.

Section VII.--Section VII (stations 139 to 143) represents a north and south section in the central part of the Pacific, and follows approximately the meridian of 160° between latitudes 34° and 22°. In this section the convection layer for the most part has a thickness of about 50 meters, varying from about 40 meters at station 143 to about 70 meters at station 140. At the last-named station the greatest accumulation of warm water is found, and the isotherms of the upper layers rise both to the north and to the south of the station. At greater depths the highest temperatures are found more to the north.

A small accumulation of water of high salinity is shown with its center at station 140 where the salinity reaches 35.3 per mille at about 200 meters; but the most conspicuous feature is represented by the tongue of water of salinity below 34.00 per mille extending almost to station 140. Even at station 139 a minimum below 34.1 per mille is found. The axis of the lowest values sinks toward the south in the most northern part of the section and rises continuously in the southern part. In the northern part it follows the isotherm of 6° at a level of about 600 meters, but to the south of station 141 the axis rises more rapidly than the isotherms and lies at a depth of 400 meters at station 139 where the temperature is 8°.

In the deep water both the temperature and the salinity appear to decrease toward the north. The decrease of the temperature is undoubtedly a real feature, but the decrease of the salinity toward the north below the 2000-meter level is so small that it lies within the limits of accuracy of the observations.

Section XIV.--Section XIV (stations 130 to 140) runs from San Francisco to the Hawaiian Islands in a direction

which changes from southwest to west-southwest. The eastern part of this section off the American coast has already been discussed because stations 130 to 134 were used when construction Section V.

The convection layer is thin at all the stations of the section, remaining, as a rule, thinner than 40 meters. Water of a temperature higher than 25° is found directly below the surface to the west of station 136. Below the warm surface layer the temperature decreases rapidly with increasing depth. The isotherm of 10° is met with at a depth of almost 400 meters at station 140: it rises slowly when approaching the American coast, and directly off the coast a rapid rise takes place, indicating an accumulation of cold water.

The low surface salinities off the coast have already been discussed. Proceeding toward the west, we find increasing surface salinities and values above 35.00 per mille at stations 137 to 140. The lowest salinities in this region are found at a depth of about 400 meters where the values lie between 34.00 and 34.1 per mille. The axis of the salinity minimum in the western part of the section shows minor bends up and down and follows, on the whole, the isotherm of 8°, which also oscillates up and down in a corresponding manner. The axis rises when approaching the coast, and we can regard it as following practically the same isotherm to the coast if, in the region where the salinity decreases with increasing depth, we take the value 33.95 per mille as the characteristic value of this intermediate water. The feature which should especially be emphasized is that between stations 136 and 140 this intermediate water has a salinity above 34.00 per mille and a temperature of 8° and is found at a level of 400 meters. The rise of the intermediate water as it approaches the coast should also be borne in mind.

The deep water, as previously, shows a nearly uniform temperature which decreases toward the bottom. The variations in a horizontal direction are small and appear to have an irregular character. The salinity increases slowly with depth and at the 2000-meter level no differences in a horizontal direction are perceptible.

Section XV.--Section XV (stations 142 to 146) represents a very short section which runs east and west in approximately latitude 33°. The convection layer again has a thickness of less than 40 meters. The isotherms are almost horizontal and the temperature decreases to less than 10° within the upper 300 or 400 meters.

The surface salinity is lower than 35.00 per mille at all stations except 144, and the salinity decreases with increasing depth. In the eastern part of the section several irregularities, intermediate minima and maxima, occur which indicate more or less complicated currents. A very pronounced salinity minimum with values below 34.00 per mille is shown at all stations. The axis of the lowest value rises considerably from west to east, lying at a depth of about 600 meters at station 142 and at a depth of 550 meters at station 146. It follows almost exactly the isotherm of 7° running slightly below this isotherm to the west of station 144 and slightly above this isotherm to the east of station 145.

Comparing the characteristics of this intermediate water with those of the corresponding water at stations 136 to 139 of the preceding section which lies about 10° farther south, we find that the layer of water of low salinity rises toward the south and that the salinity and the temperature of this water increase together. In both sections we find the intermediate water at a lower level

when the distance from the American Continent is greatest.

Section VI.--Section VI, comprising stations 125 to 130, runs from latitude 51° 58' north, longitude 150° 39' west to San Francisco. The convection layer is thin and reaches a thickness of more than 50 meters at station 129 only. The surface temperature increases as one proceeds to the southeast, and remains practically constant from station 128 to the coast. The decrease of temperature with increasing depth is rapid in the most northern part, especially at station 125 where temperatures higher than 6° are found above 45 meters only. The high surface temperatures in this region appear to be the result of heating in summer. On the whole, the subsurface temperature increases toward the southeast as shown by the sinking of the isotherms in this direction. Down to a depth of about 300 meters between stations 129 and 130, however, the isotherms rise, indicating the accumulation of cold water at the coast. The observations at stations 129 and 131, combined with the data from station 130, thus reveal the same features. The sinking of the isotherm of 5° is, on the other hand, especially rapid between stations 129 and 130, suggesting a downward motion of the water at a depth of about 600 meters. A corresponding divergence of the isotherms was found between stations 68 and 71 off the coast of South America.

The surface salinities are very low at all stations, being less than 33.00 per mille in the northwestern part of the section. A rapid increase takes place at a depth of about 150 meters and below this depth the salinity increases more slowly. It is noteworthy that the increase with depth is slow at a level of about 500 meters except at the most northwestern stations. The value of the salinity in the interval having slow increase is between 33.9 and 34.1 per mille, and the temperature ranges from 7° to 3°.5 at station 127, and from 8° to 6° at station 130. It is probable that at this depth we find the water, which, in the more southerly sections, represents the intermediate water. Between stations 129 and 130 the isohalines rise at all levels and thus give no indication of a downward movement at a level of 500 meters as suggested by the course of the isotherms at this layer.

The deep water appears to be very uniform. The 2° isotherm runs practically horizontally at a level of 2000 meters, and at this depth a uniform salinity of slightly more than 34.6 per mille is found.

After this brief description of the vertical distribution of temperature and salinity in the eastern part of the North Pacific, we turn to the conditions in the western part.

Section VIII.--Section VIII (stations 94 to 104) runs mainly in a southeasterly direction from latitude 20° 12' north, longitude 161° 19' east to the Samoan Islands. The section thus crosses the equator and, therefore, shows a number of features which are similar to those in the southern part of Section V. When examining the section it must be borne in mind that the northern part runs almost from east to west and variations which are characteristic for the north-south direction, therefore, appear much exaggerated in our representation. This is evident from figures 32 and 33, for instance, in which the observations at stations 95 to 104 have been used for the construction of true north and south sections.

The convection layer has a thickness of 50 meters or more at the northwestern station and reaches almost 100 meters at station 99. At station 98, which is located

practically at the equator, 0° 18' north, the thickness is also very great and may perhaps be taken as almost 150 meters. South of the equator the thickness is of the order of 50 meters.

The surface temperatures are above 25° at all stations. The isotherm of 20° runs at approximately the same depth at the northern and southern stations, but rises toward the surface at station 100. The course of the isotherms between stations 102 and 97 is very similar to the course of the corresponding isotherms in Section V between stations 150 and 157. Between the levels of 150 and 300 meters the lowest temperatures occur at station 100, but between 300 and 1500 meters we find the highest temperatures at this station. In still greater depths the temperature maximum shifts toward the south as in Section V. The isotherm of 5° rises more rapidly toward the north than toward the south as was the case in Section V.

The distribution of the salinity is also similar in the two sections, but in Section VIII it is more symmetrical than in Section V. At the surface, values below 34.6 per mille are found between stations 101 and 100. From the region of low surface salinity values we find increasing values both to the northwest and the southeast, but the maximum values are found at some distance from the surface. The tongues of maximum salinity at a depth of about 150 meters indicate a transport of water of high salinity toward the equator, whereas the low surface salinities perhaps can be attributed to a transport of water of low salinity away from the region of low salinity to the north of the equator. At intermediate depths we find a layer of low salinity. The salinity minimum is especially well developed to the northwest where the lowest values, less than 34.20 per mille, are found at stations 103 and 104 at a depth of about 600 meters. The salinity increases toward the southeast and the axis of the minimum values rises in the same direction, following more or less the course of the isotherms, but rising more rapidly than the latter. The temperature at the level of the salinity minimum, therefore, is between 6° and 7° at station 104, but about 8° between stations 101 and 102. Between stations 100 and 101, the layer of minimum salinity appears to diverge in two branches, one which penetrates almost to the surface at station 100, and one which is directed downward. This divergence is not very clearly seen in this section but appears better when the stations are plotted as if they were lying on a north and south line (figs. 32 and 33). A corresponding divergence was much more pronounced in Section V. To the southeast we find minimum values of the salinity of between 34.40 and 34.50 per mille at stations 94 to 97. The minimum is not sharp and the axis of the lowest values, therefore, cannot be determined with any great accuracy. It appears to lie at a level of about 800 meters, and follows the isotherm of 5°. At stations 159 and 162 (Section V) the minimum salinity was found at nearly the same level and the temperature was again approximately 5°.

The salinity distribution which is shown in this section agrees well with the section which Wüst (1929) has constructed for a region farther west, mainly by means of observations on the Planet. Wüst's section extends from latitude 15° north to 35° south, and shows especially that the current, which at a depth of 150 to 200 meters carries water of high salinity toward the equator, submerges between latitudes 25° and 30°. Wüst's section reaches to a depth of 600 meters only. Between latitudes

15° and 10° north the layer of minimum salinity rises from 500 meters to about 350 meters and to the south of 10° north it divides into one ascending and one descending branch in agreement with what we have found. The salinity minimum to the south of the equator is not shown in Wüst's section because it lies at a greater depth.

The deep water, as usual, is very uniform. The temperature decreases to the greatest depth from which observations are available, approximately 3000 meters, and at this level is highest in the southeastern part of the section. The salinity is, on the whole, higher than 34.60 per mille below a level of about 1700 meters and increases with depth as far as the observations go.

Section XIII.--Section XIII (stations 101 to 107) includes stations 101 to 104, which were used in Section VIII, and runs mainly in an east and west direction between longitudes 178° and 146° east. The section forms a regular curves toward stations 101 and 107, however, lying in latitudes 13° 23' and 14° 05' north, respectively, whereas station 104 lies in latitude 20° 12' north. This curvature toward the north, as presently will be seen, determines the characteristic vertical distribution of temperature and salinity which appears in the section.

The convection layer reaches to at least 50 meters at all stations and at some of them has a thickness which probably approaches 100 meters. The temperature section shows the greatest accumulation of warm water in the central part of the section, but this circumstance must be attributed to the fact that the central part lies in a higher latitude than the eastern and western parts. The downward curvature of the isotherm of 10° is, therefore, not related to a change in an east and west direction but to a change in a north and south direction. The isotherms of 5° and less, on the other hand, have their highest position in the central part of the section and the curvature of these isotherms must be related to to the fact that at greater depths the temperature increases from north to south.

The courses of the isohalines show a vertical distribution of the salinity, which agrees perfectly with the vertical distribution of temperature. The highest surface value of the salinity is found at the most northern station, 104. Below the surface on both sides of this station we find a layer of higher salinity which must be related to the subsurface transport of water of high salinity toward the equator. The intermediate salinity minimum is most pronounced and is found at the greatest depth at station 104. The axis of the minimum values rises to both sides, and the values themselves increase. The axis rises more toward the southeast and southwest than do the isotherms. In the central part the axis lies at a depth of 650 meters where the temperature is 6°, but at the most southeastern station the minimum is found at 450 meters where the temperature is 8.°5, and at the most southwestern locality the minimum lies at 400 meters where the temperature is 9°. The only conclusion which can be drawn as to variations in an east and west direction, however, is that the salinity minimum layer appears to lie higher and the temperature is higher at the most western station--107--than at the most eastern station--101.

It is of interest in this connection to point out that at station 149 (Section V), which lies in almost the same latitude as station 104, we found a salinity minimum at a depth of 350 meters where the temperature was 9°. When discussing sections XIV and XV it was shown that the minimum layer apparently sinks toward the west and

this conclusion appears to be verified when one compares conditions at stations 104 and 149.

The deep water is again of a uniform character. The temperature decreases and the salinity increases with increasing depth as far down as observations have been carried out.

Section IX.--Section IX, comprising stations 107 to 120, is actually composed of two different sections, one running southwest from latitude 47° 02' north and longitude 166° 20' east to the coast of Japan off Yokohama, and one running north and south following practically the meridian of 144° east between latitudes 35° and 14° north. We shall discuss the latter part of the section first.

The convection layer has a thickness of about 50 meters at the southern stations of the section, but at the northern stations it has a thickness of less than 40 meters.

Temperatures above 25° are found at the three southern stations only, but the isotherm of 10°, except for some undulations, runs almost horizontally at a level of approximately 500 meters, but between the two most southerly stations it rises distinctly toward the south. In this most westerly section we thus find the greatest accumulation of warm water in the upper layers, but in the deeper layers the temperatures are higher at the southern stations. Between 500 and 1000 meters the isotherms diverge toward the south.

The surface salinity has values above 35.00 per mille between stations 108 and 109 only. Values above 35.1 per mille are found between 150 and 200 meters in the most southern part of the section, indicating a transport of water of high salinity from the surface region of high salinity located to the northeast. At a depth of about 500 meters the isohaline of 34.2 per mille runs almost horizontally, undulating up and down, and corresponding to the course of the isotherm of 10°. A conspicuous rise toward the south is found between stations 107 and 108 corresponding to the rise of the isotherms between these stations. The layer of minimum salinity can be followed at all stations to the south of station 113. Between stations 109 and 113 the axis of the minimum value lies at a level of 650 meters where the temperature is about 6° and rises to 8°.5 at a depth of 450 meters at station 107 to the south of station 109. Comparing these conditions with the corresponding conditions in Section VII in the same latitude, we find that the layer of minimum salinity probably lies somewhat deeper in the most western part of the ocean.

In the deep water the temperature, which decreases very slowly toward the north, decreases with increasing depth; and the salinity, which below a level of about 2000 meters is slightly above 34.6 per mille, increases with depth.

In the northeastern part of Section IX we find a quite different stratification. The convection layer is very thin, especially at the northeastern stations where it perhaps has a thickness of 10 meters only.

The most conspicuous feature of the vertical distribution of temperature is the very rapid change in the character of the temperature distribution between stations 112 and 116. The isotherms rise rapidly toward the north in a manner which reminds one of the rise of the isotherms toward the north on the southern side of the Grand Banks of Newfoundland in the Atlantic. Between stations 115 and 116 we find a "cold wall." The change in the temperature distribution, however, appears

to be of an irregular character and from the course of the isotherms, it seems that whirls are formed along the boundary between the warm water to the south and the cold water to the north. The great temperature contrasts are present down to a level of 500 meters. Below this level the contrasts gradually get smaller and at 1000 meters the temperature difference has been reduced to 1°. At 2000 meters practically nothing is left.

Between stations 112 and 116 the salinity decreases as rapidly as the temperature. The great irregularities in the distribution of the salinity strongly support the opinion that whirls of great dimensions are formed at the boundary between the warm water of high salinity to the south and the cold water of low salinity to the north. The lowest surface salinities are found at the most northeastern stations 119 and 120 where the values are below 33.00 per mille.

The great contrast between the salinities of the upper layers can be followed to a depth of about 500 meters, but below this level it almost disappears. It is of interest in this connection to note that to the north of station 116 the isohaline of 34.00 per mille lies at a level of approximately 400 meters where the temperature is somewhat above or somewhat below 4°. It also is of interest to note that a downward transport of water, which has the same character as the intermediate water of low salinity in the southern part of the section, apparently takes place only between stations 115 and 116, and that a downward transport of such water can hardly be traced at the northeastern stations.

The deep water has the same characteristics as in the southern part of the section. Taking the section as a whole, we find a tendency toward decreasing temperature and decreasing salinity as we proceed toward the north at a level of about 2000 meters.

Section XVI.--Section XVI (stations 118 to 125) runs west-southwest from latitude 51° 58' north and longitude 150° 39' east to 42° 29' north and 155° 24' west. In the eastern part the section bends slightly toward the north. On a short stretch it runs along the Aleutian Islands and continues at last in a southwesterly direction. The convection layer is very thin at all stations, especially in the western part of the section where it is of the order of 10 meters only.

Below the topmost surface layer we find between stations 119 and 123 a layer of minimum temperature at a level of about 100 meters. At stations 119 and 120 the temperature within this layer is below 2° and farther to the east values smaller than 3° are found. This water of very low temperature probably comes from the Bering Sea where it has been formed in the preceding winter and from where it has entered the Pacific Ocean, and partly spread toward the east. At greater depths the temperature decreased regularly as far down as the observations were made.

The salinity is very low at the surface and increases with depth at all stations except at station 118 where some irregularities are found above 200 meters. The increase of the salinity is especially rapid down to the 200-meter level. From there the increase continues at a slow rate and the value 34.°6 is reached somewhat below the 2000-meter level.

It should be pointed out especially that in this section we find no layer of minimum salinity. Furthermore, we find no water masses which have the characteristic temperature and salinity of the intermediate water in the southern sections, namely, 6° and 34 per mille. The

water which has a salinity of 34.00 per mille has a tem-
perature of about 3°, and water having a temperature of
6° has a salinity which is smaller than 33.5 per mille.

The deep water is again of a uniform character, but
appears to be somewhat cooler than the deep water at
corresponding depths in the equatorial region. Thus the
isotherm of 2° lies at a depth of about 1700 meters in
Section XVI, but at the equator it lies at a depth of about
2300 meters. The salinity of the deep water appears to
be smaller than in the most northern region; the depth
of the isohaline, 34.6 per mille, is about 2300 meters in
Section XVI, but at the equator it is about 1600 meters.

Distribution of Density

The horizontal and vertical distributions of density,
t, have been represented in figures 234 to 245; I-B and
96, 102, 108, 114, 120, 129, 135, 144, 150, 156, 162, 168,
174, 180, 189, and 198; I-B, respectively. When prepar-
ing these the course of the isotherms and isohalines was
taken into account. We shall not enter into details but
only draw attention to the most prominent features.

When examining the figures showing the horizontal
distribution, it should be borne in mind that at any level
the movement of the water, relative to the directly under-
lying water, takes place in such a direction that in the
Northern Hemisphere one has the light water on the
right-hand side, and in the Southern Hemisphere the
light water on the left-hand side.

Surface.--Here we find the lowest densities on both
sides of the equator in low latitudes. The belts of low
density are separated from each other by a region of
higher density where, however, the values are only a
little above the values to the north and to the south. To
the north of the region of low density in the Northern
Hemisphere the density increases rapidly with increas-
ing latitude. This increase is regular except in the re-
gion off the coast of California and at the coast of Japan.
In the Southern Hemisphere the density appears to in-
crease toward the coast of South America and toward the
south, but within a great area off the coast of South
America the density remains practically constant. Along
the coast of Central America the surface density is very
small within a limited region.

One hundred-meter level.--At this level the region
with minimum density to the north of the equator partly
has been replaced by a region of very high density. To
the north of latitude 20° north the density increases to-
ward the north except in the region off the coast of Cali-
fornia where a rapid increase toward the coast takes
place, whereas the densities are low off the southern
coast of Japan. In the Southern Hemisphere the increase
toward the coast of South America and toward the south
are the most conspicuous features. The low densities
along the coast of Central America have disappeared.

Two hundred-meter level.--Here the development
has continued in the same direction. The region of max-
imum density to the north of the equator, however, is
less pronounced but stretches across the ocean. Two
regions of minimum density are under development in
latitudes 20° north and 17° south, and from the former
there is a general increase toward the north and toward
the coast of California. The low densities off the south-
ern coast of Japan are still conspicuous. In the Southern
Hemisphere the increase of density toward the south is
more prominent than the increase toward the coast of
South America.

Three hundred-meter level.--Here the high densities
in the equatorial region show a stripe-like distribution.
The density minimum in latitude 20° north is the domi-
nant feature in the Northern Hemisphere. A correspond-
ing minimum is probably developed in the same latitude
in the Southern Hemisphere, but the observations are
not extended over a sufficiently wide area to show the
entire minimum.

Four hundred- and five hundred-meter levels.--At
these levels we find practically the same distribution as
at the 300-meter level. An area of high density covers
the equatorial region to almost 20° south and 20° north,
and the stripe-like distribution is still seen. In the
Northern Hemisphere the minimum is being displaced
more and more toward the north. At these levels and at
the 300-meter level the low density off the southern
coast of Japan still prevails.

Seven hundred-meter level.--Here the distribution
in the Northern Hemisphere is the same as before, ex-
cept that the minimum has shifted farther north, but in
the Southern Hemisphere we find a decrease of the den-
sity toward the south at the most southerly stations. At
these stations the direction of the relative current thus
seems to be reversed. Above the 700-meter level the
relative current is directed toward the coast; below the
700-meter level it appears to be directed away from the
coast.

One thousand-meter level.--The differences in den-
sity have decreased regularly downward and at this level
are very small, but in the Northern Hemisphere the dis-
tribution has remained more or less unaltered. In the
Southern Hemisphere the decrease of the density toward
the south at the most southern stations is more pro-
nounced than at the 700-meter level. In latitude 20°
south we find increasing density toward the south, where-
as at the higher levels we found decreasing densities.
The relative current, which at the higher levels was di-
rected toward the west, appears at this level to be di-
rected toward the east.

Fifteen hundred-meter level.--Here the differences
in density are very small between latitudes 40° south and
and 40° north, but to the north of 40° north we find, even
at this level, an increase toward the north. This indi-
cates a relative movement toward the east as in the up-
per layers. At the southern stations off South America,
on the other hand, we still find a decrease toward the south,
which indicates relative movement toward the west.

Two thousand-, twenty-five hundred-, and three
thousand-meter levels.--Here the density is nearly con-
stant but the values appear to be lower in the Northern
than in the Southern Hemisphere.

We shall not enter on a discussion of the distribution
of the density in the vertical sections because such a
discussion would not add materially to the knowledge of
the character of the different water masses which has
been obtained by a discussion of the distribution of tem-
perature and salinity.

Temperature-Salinity (tS) Relation

The temperature-salinity diagrams for each station
in the Pacific are shown in figures 203 to 209; I-B. We
shall not enter on any detailed discussion of the charac-
teristic features of these diagrams at the single stations
but shall make use of the tS relation in order to point out
the characteristic properties of the water at different
levels and in different regions.

For this purpose we have plotted in figures 13 to 18 all observations below the 100-meter level, using vertical lines to designate the observations between 100 and 500 meters, 500 and 1500 meters, and below 1500 meters. The observations have been combined into groups which show the characteristic tS relation within certain regions. The limits of these regions have been determined by means of the tS curves and may thus be regarded as natural subdivisions. Within each region we find, on the whole, the same tS relation at the different stations, and in most cases the transition from one type of tS relation to another is quite distinct. Cases exist in which the transition from one region to another, however, takes place within an area which is so great that observations at some stations show a tS relation which lies between the characteristic relations of the two neighboring regions.

The areas within which the tS relation is nearly the same have been indicated in figure 19 in which they have been numbered from 1 to 14. Figure 20 shows the tS curves for each of these regions. The numbers of the regions are entered on the corresponding curves. The curves represent the mean curves as derived from the diagrams in figures 13 to 18 in which the single observations have been entered. From these single diagrams it is seen that within every region the water is typically stratified. Water of a low temperature is found at great depths only, water of a temperature about $3°$ to $7°$ between the levels 500 and 1500 meters, and water of a high temperature is found above 500 meters. It is possible, therefore, even on the average curve, to indicate the depth interval at which water of certain characteristic temperature and salinity is found. This has been accomplished in the average curves on figure 20 by drawing the tS curve which shows the characteristic relation below a depth of 1500 meters as a very heavy line, the curve between 500 and 1500 meters as a moderately thick line, and the curve above 500 meters as a thin line. The moderately thick line represents water which is found between 500 and 1500 meters only, but on the thin line a mark has been placed, indicating the maximum stretch along the tS curve which represents water below the 500-meter level. The part of the thin curve to the right of the mark thus represents water which never is found below 500 meters, whereas the part of the thin curve to the left of the mark represents water which may be found both above and below the 500-meter level.

It is not necessary to enter on the characteristic properties of the water below 1500 meters within the deep areas, because the water is evidently of nearly the same character within all areas. From the course of the tS curve it is evident that the deep water of the lowest temperature has the highest salinity, and also that the salinity of water of a temperature of $2°$ decreases from the south toward the north. Distinct differences between the different areas are found above the 1500-meter level and we shall discuss these more fully.

Region 1 comprises the most southern area of the Pacific which was investigated, and lies to the west of the South American coast. In this area we find a salinity minimum within the interval 500 to 1500 meters which is characterized by the corresponding values, S = 34.25 per mille, t = $5°2$. Above 500 meters we find that water of a high temperature has a lower salinity than is found at any depth below 500 meters.

Region 2 lies to the north and northwest of Region 1 and differs mainly as to the character of the water above 500 meters. The water between 500 and 1500 meters is practically of the same character as in the more southern region, but both salinity and temperature appear to have increased. The corresponding values at the salinity minimum are S = 34.29 per mille and t = $5°5$.

Regions 3, 4, and 5 lie between south latitudes $10°$ and $20°$: Region 3 off the coast of South America, Region 4 between longitudes $95°$ and $130°$ west, and Region 5 between longitudes $130°$ and $175°$ west. Region 5 extends slightly more toward the north than does Region 4. In these three regions we find practically the same tS relation in the interval, 500 to 1500 meters. The corresponding values at the salinity minimum are: in Region 3 S = 34.51 per mille, t = $5°6$; in Region 4 S = 34.52 per mille, t = $5°6$; and in Region 5 S = 34.40 per mille, t = $6°0$. Above the 500-meter level considerable differences exist between these three regions, but we have already dealt sufficiently with these differences when describing the horizontal and vertical distribution of temperature and salinity.

Regions 6 and 7 comprise equatorial areas; one, Region 6, off the South American coast, and the other, Region 7, in the central part of the Pacific. Below a depth of 100 meters we find practically the same tS relation at stations 150 to 158 and stations 98 to 100 and these have, therefore, been combined. It should be noted that the northern limit of Region 7, however, does not run east and west but approaches the equator more in the western than in the eastern part of the ocean. The tS relation below the 500-meter level is similar within regions 6 and 7, the only difference being that in Region 6 higher temperatures are found at 1500 meters. The lowest salinity values between 500 and 1500 meters are about 34.55 per mille and the corresponding temperature is $5°6$.

Regions 8 and 9 stretch together across the Pacific in a direction from east-northeast to west-southwest. Within these regions we find some differences between the tS relation in the eastern and western parts of the ocean, but the general features of the relation are similar. In the eastern part the salinity decreases more rapidly with decreasing temperature and reaches a minimum values of 33.98 per mille where the temperature is $8°$, but in the western part the decrease of the salinity is slower and a minimum value of 34.23 per mille is reached where the temperature is $9°5$.

Regions 10 and 11 to the north of regions 8 and 9 show a similar difference between the relations in the eastern and western parts of the ocean. In the eastern part the salinity decreases rapidly to a minimum of 33.97 per mille where the temperature is $6°$, whereas in the western part a more gradual decrease takes place, reaching to a minimum of 34.10 per mille at a temperature of $6°5$.

Region 12 lies off the coast of North America and northeast of Region 11. In this region the salinity decreases constantly with decreasing temperature, but the decrease is slow where the salinity has a value of 33.98 per mille and the temperature is $6°$, corresponding to the characteristic temperature and salinity at the minimum on the tS curve in Region 11.

In Region 13, which lies off the coast of Japan in latitude $40°$, and in which only the three stations--115, 116, and 117--were occupied, we find a tS relation which is rather similar to the relation in regions 10 and 11, but with greater variations. The salinity decreases rapidly with decreasing temperature to a minimum of 33.78 per

mille at a temperature of 5.°3 and at greater depths increases with decreasing temperature. The minimum value is found above the 400-meter level, and the corresponding values of temperature and salinity are both lower than the corresponding values in Region 11, but there they are found below 500 meters.

In Region 14 to the south of the Aleutian Islands and the Bering Sea we find increasing temperature with decreasing salinity up to 500 meters, but above this level the temperature remains constant at about 3.°4, whereas the salinity decreases.

It is seen that the tS curves in regions 1 and 2 and regions 10 and 11 have nearly the same form except in Region 1 near the surface. The stratification is thus of a similar character in the North and South Pacific. The transition from the tS curve in about latitudes 40° south and 40° north to the tS curves of the equatorial region is more or less similar in both hemispheres.

The Intermediate Water

The most conspicuous feature which is revealed by the curves is the existence of water of low salinity at an intermediate depth. In the Southern Hemisphere the intermediate water of the Pacific Ocean is probably being formed in the same manner as the corresponding intermediate water of the Atlantic and Indian oceans; it sinks and flows north from the region of the Antarctic convergence, which has been traced all the way around the Antarctic Continent.

If the Antarctic intermediate water follows a more or less direct course from the region where it submerges to the regions in which we have found it, we must assume that the water has a high oxygen content. Fortunately the oxygen content has been observed at two of the Carnegie stations in regions 1 and 2, namely at stations 52 and 57. At station 52 the observations show a maximum of oxygen, 5.09 ml/L, at a depth of 657 meters where the intermediate water was found. At station 57 observations are lacking for the central part of the intermediate water but at the upper part of this water, at a depth of 468 meters, the oxygen content showed a maximum of 5.47 ml/L. Thus, the intermediate water appears to have a high oxygen content in contrast with the corresponding water in the Northern Hemisphere. This high content strongly supports the opinion that the water comes on a direct route from a region where it has been in contact with the atmosphere.

In the Northern Hemisphere a convergence, corresponding to the Antarctic convergence, is not found, but we have seen, when studying Section IX, that big whirls are formed along the boundary of the warm and the cold water off the Japanese coast, and it was pointed out that within these whirls water of the typical properties of the intermediate water was found. In this region probably we must look for one of the places where a supply of water to the intermediate current takes place. It is possible that the region where such whirls are formed extends to some distance from the Japanese coast, but this extension cannot be very great, considering the general character of the currents. The water which is supplied to the intermediate current should thus be formed by mixing of different water masses in the region off Japan, but this mixing takes place below the surface, judging from the conditions which are represented in Section IX.

The mixing appears to take place between water of low temperature and low salinity coming from the north, perhaps from the upper layers, and warmer water of higher salinity which is carried from the south by subsurface currents. Therefore, part of the water which supplies the intermediate current has not been in direct contact with the atmosphere and must consequently contain a relatively small amount of oxygen. Such processes would explain the fact that the oxygen content of the intermediate water in Region 11 is of the order of between 2 and 4 ml/L. In this region the oxygen content of the intermediate water generally decreases with increasing depth, but a secondary maximum between 300 and 400 meters at stations north of latitude 20° north in indicates an admixture of surface water.

The Deep Water

Temperature and salinity.--When discussing the horizontal and vertical distribution of temperature and salinity, we pointed out that the deep water is of a very uniform character. The temperature lies between 1.°5 and 2°, and the corrected salinity between 34.65 and 34.73 per mille. Our horizontal representations went down to a level of 3000 meters. It is of interest to examine the few observations which are available for greater depths. At several stations observations with intervals of about 500 meters were taken below the 3000-meter level. At a great number of stations the temperature at the bottom was measured, but in these cases no water samples were obtained for determining the salinity.

Table 9 gives the mean temperatures and salinities within the regions into which the ocean was divided on the basis of the tS relations. The mean values have been computed for the intervals 3000 to 3500, 3500 to 4000, 4000 to 4500, and below 4500 meters. From the last interval only temperature observations are available, and from the interval 4000 to 4500 meters salinity observations are present from regions 4 and 6 only.

It is seen that the temperature is very uniform in the great depths of the North Pacific where the greatest difference between any of the mean values from the different depths and different regions amounts to only 0.°24. The temperature appears to increase slightly toward the bottom within some of the regions and later we shall return to this feature.

In the South Pacific we find, on the other hand, considerable variations both in a horizontal direction and with depth. The highest temperature is found in Region 6 near the equator off the coast of South America and off the coast of Peru where the temperature is constant between 3000 and 4000 meters. In Region 5 in the central part of the Pacific in latitude 15° south and in the most southern region--1--the temperature decreases with increasing depth.

The salinity appears to decrease from the Southern to the Northern Hemisphere but within each region the variations in a vertical direction are so small that they are within the limits of the accuracy of the observations. The values in the table should probably be increased by 0.03 per mille (see p. 72).

Bottom temperature.--The bottom temperatures at depths greater than 3000 meters have been entered in table 10 and figure 21. The values underscored in the figure refer to depths between 3000 and 4000 meters. In the South Pacific high bottom temperatures are found in the eastern part but here no observations from depths

Table 9. Temperatures and salinities below 3000 meters in stated regions and intervals of depth

Depth in meters	Region													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Temperature °C														
3000-3500	1.52	1.86	1.82	1.83	1.66	2.09	1.59	1.68	1.55	1.55	1.54	....	....	1.57
3500-4000	1.23	....	1.82	1.57	1.51	....	1.46	....	1.52	1.46	1.51	1.58	....	....
4000-4500	....	....	....	....	1.33	....	....	....	1.55	....	1.53	1.56	....	....
4500	....	....	....	....	1.21	....	1.44	....	1.52	1.49	1.61	....	....	....
Salinity °/oo *														
3000-3500	34.68	....	34.67	34.67	34.66	34.62	34.66	34.64	34.64	34.62	34.62	....	....	34.63
3500-4000	34.65	....	34.68	....	34.66	....	34.64	....	34.64	34.63	34.65	....	....	....
4000-4500	....	....	....	....	....	....	....	....	34.64	....	34.65	....	....	....

*Values probably 0.03 °/oo too low.

greater than 4000 meters are available. The lowest bottom temperatures are found to the south of the equator at stations 160 and 161 in about latitude 13° and longitude 167°. The values of temperature at these stations are 1°09 and 1°08 at the depths 4444 meters and 5084 meters respectively. Between the equator and latitude 20°, and in longitude 140° west, the bottom temperatures lie between 1°4 and 1°5, but to the north of latitude 20° we find values above 1°5 in the entire region except at two stations off the coast of Japan, where lower temperatures are found. At two stations--141 and 142--to the northwest of the Hawaiian Islands, temperatures are above 1°6, but other than these exceptions the bottom temperatures appear to be very uniform.

When discussing the mean temperatures at different depths and within different regions, we pointed out that the temperature increases with depth in some regions. Examining the data from the single stations, we find only four stations at which a decided increase of temperature with depth takes place, namely, stations 37, 135, 142, and 146.

Table 11 gives the observed temperatures at these stations, the potential temperatures (see p.32) the salinities, and the oxygen content. Station 37 is located off the coast of Central America, and here the increase of temperature with the depth is so considerable that the potential temperature is constant. The decrease of the salinity from 34.65 per mille (34.68) at 2730 meters to 34.63 per mille (34.66) at 3231 meters is so small that we cannot give any weight to this difference. We must assume that the salinity is constant, and the constant potential temperature then indicates that indifferent equilibrium exists below a level of 2700 meters.

Stations 135, 142, and 146 are all taken in nearly the same region. At these stations the temperature increases with depth, but the potential temperature decreases and at the same depth is very nearly the same at the different stations. The salinity, on the other hand, appears to be constant. The variations must be ascribed to accidental errors of observation because, combining observations from five stations in this region, we find the salinities 34.638 (34.668), 34.650 (34.680), and 34.644 (34.674) per mille at the depths 3100, 3700, and 4100 meters, respectively; that is, practically no variation with depth. The equilibrium must, therefore, be stable. At a few other stations in this same region we find an indication of a temperature minimum at a depth of 3700 meters, but the increase below this level is smaller than 0°05 and therefore the stratification is still more stable at these stations. Helland-Hansen (1930) has shown that

Table 10. Bottom temperatures of water, bottom depths greater than 3000 meters, Pacific Ocean, Carnegie, 1929

Station	Latitude	Longitude West	Depth Thermometer	Depth Bottom	Temperature
	° '	° '			°C
49	23 16 S	114 45	3098	3098	1.86
76	15 18 S	97 28	3181	3197	1.84
82	14 52 S	126 07	3596	3631	1.57
83	17 00 S	129 45	3921	3966	1.55
84	17 11 S	133 18	4076	4121	1.51
85	17 12 S	136 37	3746	3791	1.53
87	18 05 S	145 33	4270	4315	1.40
110	26 20 N	215 36	2996	3036	1.49
111	31 00 N	215 44	5978	6008	1.49
112	33 51 N	218 45	3901	3931	1.41
115	37 40 N	214 34	5360	5396	1.55
116	38 41 N	212 19	5513	5545	1.53
117	40 20 N	209 02	5261	5296	1.56
119	45 24 N	200 24	5170	5198	1.54
127	44 16 N	137 37	4004	4026	1.56
128	40 37 N	132 23	3796	3806	1.58
131	33 49 N	126 20	4388	4418	1.55
132	31 38 N	128 48	4221	4251	1.55
133	29 21 N	132 30	4396	4426	1.57
134	27 45 N	135 22	4498	4528	1.58
135	26 39 N	139 07	4660	4695	1.56
137	24 02 N	145 33	5268	5208	1.52
138	22 53 N	151 15	5342	5382	1.52
139	21 47 N	155 31	4990	5030	1.49
140	23 26 N	159 27	4722	4762	1.55
141	29 02 N	161 11	5627	5667	1.63
142	32 42 N	160 44	5747	5787	1.65
146	31 51 N	140 50	4716	4756	1.55
148	24 57 N	137 44	4795	4835	1.50
149	21 18 N	138 36	5280	5320	1.53
150	16 15 N	137 06	4513	4553	1.44
151	12 40 N	137 32	4878	4918	1.49
155	4 51 N	146 46	5273	5304	1.44
156	3 01 N	149 46	4913	4953	1.39
159	9 24 S	159 01	5505	5545	1.34
161	12 04 S	164 57	4444	4484	1.09
162	13 36 S	168 23	5084	5124	1.08

in the eastern North Atlantic the potential temperature is constant below a level of 4000 meters, whereas in the western North Atlantic it decreases toward the bottom.

A constant potential temperature over a wide area is generally attributed to the influence of heating from below, from the interior of the earth, and it is assumed that the horizontal currents must be very slow where a constant potential temperature can be developed. Examples of a constant or even a downward increasing potential temperature are known from the deep basins in the region of the East Indian Islands, and here one probably finds stagnating water in the great depths. The fact that the potential temperature appears to decrease toward the bottom in the North Pacific indicates that the bottom water is not stagnating but is being renewed. The relatively high oxygen content and the increase of this content toward the bottom strongly support the opinion that a renewal of the bottom water by horizontal transport takes place. The low bottom temperatures in the South Pacific point toward a more rapid renewal of the bottom water in this part of the Pacific. No oxygen observations are available from these stations and therefore we are unable to obtain a verification of our conclusions.

The origin of the deep water of the Pacific has been discussed previously (Sverdrup, 1931). It was pointed out that the deep water cannot be formed by the sinking of surface water in the central part of the ocean (combined with processes of mixing) because the deep water is separated from the surface water by a layer of minimum salinity. It was also shown that the deep water could not be formed in the neighborhood of the Antarctic Continent because the temperatures are too high. We may add that, for the same reason, the deep water cannot come from the Bering Sea. Furthermore, it is not probable that bottom water of low temperature is formed in the Bering Sea by the processes which have been described by Nansen, because the surface salinities in the Bering Sea appear to be too low, if we judge from the salinity of the surface current which enters the Pacific Ocean.

The available data strongly point in the direction that water of the same type as the deep water of the Pacific is formed in the eastern part of the Indian Antarctic Ocean and that the origin of the deep water of the Pacific has to be sought there. In order to explain this formation, it was assumed that Antarctic bottom water

of low temperature and relatively high salinity was formed everywhere on the continental shelf of the Antarctic Continent. This water would sink to great depths and contribute toward the formation of cold bottom water which would tend to spread toward the north but, owing to the rotation of the earth, would be deflected to the left and flow along the continent from east to west. A complete circumpolar flow would, however, not be developed since the submarine ridge between South America and the Antarctic Continent would present a serious obstacle to a flow of the bottom water toward the west. In the region of the Weddell Sea the bottom water, therefore, would be deflected toward the north and a great part of this water would enter the western basin of the South Atlantic Ocean. Furthermore, it was assumed that this inflow of cold bottom water was in part responsible for the outflow from the Atlantic of warmer and more saline deep water at some higher level. This flow of Atlantic deep water must also be deflected toward the left which, in this case, means to the east, and the Atlantic deep water must, therefore, enter the Indian Ocean as pointed out by L. Möller (1929) and clearly demonstrated by Wüst (1935). In the Antarctic Ocean to the south of the Atlantic and the Indian oceans, mixing between these two types of water, the cold Antarctic bottom water and the warmer Atlantic deep water, must take place and, as a result of these processes of mixing, a water type is formed which is similar to the deep water of the Pacific. It was assumed that this water enters the Pacific through the passage between New Zealand and the Antarctic Continent.

This hypothesis concerning the formation of the deep water of the Pacific was advanced at a time when no reliable deep-sea observations were available from the vicinity of the Antarctic Continent except in the Weddell Sea area. Since that time a considerable amount of oceanographic work has been carried out on the expeditions with Discovery II, on the British Australian New Zealand Antarctic expeditions conducted by Sir Douglas Mawson, and on the Norwegian expeditions organized by Mr. L. Christensen. The observations from these various expeditions have not yet been published,[1] but the writer has had opportunity to examine the results from the British Australian New Zealand Antarctic expedition and to become acquainted with results from L. Christensen's cruises. The new information necessitates considerable modification of the views which were presented in 1931 but the most important conclusion, that the deep water of the Pacific Ocean is formed in the Antarctic Ocean and enters through the passage between New Zealand and the Antarctic Continent, remains unaltered.

It is now evident that a considerable formation of Antarctic bottom water takes place only within the area of the Weddell Sea. H. Mosby (1934) has shown that the bottom water in the Weddell Sea is formed by mixing of deep water (temperature about $1°$ C and salinity about 34.70 per mille) and water from the continental shelf which has been cooled to freezing point (about $-1°85$ C) and which has attained a salinity of about 34.60 per mille, owing to the processes of freezing. The resulting bottom water has a temperature of about $-0°6$ C and

Table 11. Stations at which a decided temperature increase toward the bottom was observed.

Station	Depth		Temperature		Salin-ity* °/oo	Oxygen content ml/L
	Bottom meters	Obs'n. meters	Obs'd. °C	Poten. °C		
37	3324	2730	2.05	1.84	34.65	.....
		3231	2.10	1.84	34.63	.....
		3324	2.12	1.85	....	.....
135	4695	3301	1.52	1.26	34.64	2.92
		3736	1.51	1.21	34.65	3.11
		4098	1.53	1.19	34.63	3.15
		4660	1.56	1.15	....	.....
142	5787	3268	1.54	1.28	34.60	2.83
		3682	1.52	1.22	34.64	3.23
		4043	1.53	1.19	34.62	3.29
		5747	1.65	1.09	....	.....
146	4756	3159	1.54	1.31	34.65	2.23
		3610	1.50	1.21	34.66	3.11
		4069	1.51	1.17	34.65	3.11
		4486	1.55	1.16	34.65	3.40
		4716	1.55	1.13	....	.....

*Values probably 0.03 °/oo too low.

[1]The observations in physical oceanography in the British Australian New Zealand Antarctic expedition have been published by A. Howard (1940) and have been discussed by H. U. Sverdrup (1940).

à salinity of about 34.66 per mille, and it shows a high oxygen content since the water on the shelf is nearly saturated with oxygen. Along the Antarctic coast of the Weddell Sea the flow of the water is directed toward the west and the westward motion of the waters can be traced as far east as the region of Enderby Land. This westward flow represents the southern part of a big eddy which characterizes the entire Weddell Sea region.

The observations from the Australian Antarctic expeditions and from L. Christensen's expedition with the Thorshavn show that sinking of water from the continental shelf does not contribute materially to formation of bottom water within the entire region from Enderby Land and eastward to Drake Passage and they show, furthermore, that the flow of the deep water is directed toward the east within the entire region. From observations at a few stations it is evident that water from the shelf intermittently sinks to great depths but in small quantities only, for which reason the character of the bottom water is only slightly influenced by these processes. The previous hypothesis of the writer, that bottom water was formed all around the Antarctic Continent and that a flow of bottom water toward the west took place in every region, must therefore be abandoned. It is probable that the surface waters near the continent flow toward the west, but within the deep water there evidently exists an Antarctic circumpolar current which flows toward the east and follows the continent (except in the region of the Weddell Sea) as far east as Enderby Land, where a big eddy occurs on the southern side of the circumpolar current.

The characteristic properties of the water masses within this circumpolar current are mainly determined by the deep-water flow in the Atlantic Ocean, including the Weddell Sea area. The deep-water flow within the Atlantic Ocean has recently been discussed by Wüst (1935) who has shown that three areas exist within which the surface waters attain such a high density that they must sink and contribute to the renewal of characteristic water masses at great depths. One of these areas is represented by the Mediterranean. Water of very high salinity flowing out from the Mediterranean mixes with Atlantic water and spreads toward the north and the south, where it can be traced as an upper deep water. A second area is found in the waters between Iceland, Greenland, and Labrador. Within this area Atlantic water of relatively high salinity is mixed with Arctic water and cooled to such a low temperature that in some localities water is formed which is of uniform density from the upper layers to the bottom. Here water from the upper layers may sink to great depth and contribute to the renewal of the Atlantic lower deep water (mittleres Tiefenwasser, according to Wüst's terminology) which can be traced to latitude 55° south. Within this region or farther north, conditions may favor the development of a water of lower temperature and lead to formation of the bottom water of the North Atlantic, but this type of water does not spread to any considerable distance and is, therefore, of minor importance. The third area is within the Weddell Sea, where the Antarctic bottom water is being formed in the manner which has been described. This bottom water spreads toward the north and can be traced to latitude 40° north.

Within the Atlantic Ocean we find, therefore, an "active" deep-water circulation, especially between the sea to the south of Greenland where the Atlantic lower deep water is formed, and the area of the Weddell Sea where the Antarctic bottom water originates. No such "active" deep water circulation is present in the other oceans. In the Indian Ocean water from the Red Sea spreads at moderate depths, but is of much less importance than the Mediterranean water in the Atlantic. Water corresponding to the Atlantic lower deep water is not formed in the Indian Ocean nor is Antarctic bottom water formed south of the Indian Ocean. Within the entire area of the Pacific Ocean no renewal of any type of deep water takes place.

The water masses of the Antarctic circumpolar current are, as already mentioned, formed by mixing of Atlantic deep water and Antarctic bottom water. Wüst has shown that such processes of mixing take place to a great extent in the Atlantic Ocean, and he has computed the percentage amount of true Atlantic deep water or true Antarctic bottom water in the layers of the Atlantic Ocean. The two types of water are still characteristically different within the circumpolar current in the southern part of the Atlantic Ocean, but when carried toward the east by this current the differences disappear, owing to processes of mixing, and to the south of Australia we find water of a very homogeneous character which can be described as a special type of water, the Antarctic circumpolar water. The temperature of this water lies between 0° and 2° and the salinity between 34.68 and 34.74 per mille.

This water flows, as already stated, around the entire Antarctic Continent and follows the continental slope except in the region of the Weddell Sea where there is a large eddy south of the circumpolar current. This is evident from the observations of the Australian Antarctic expedition, and Clowes (1933) has convincingly shown that the flow through Drake Passage is directed from the Pacific to the Atlantic Ocean. Accurate determinations of the oxygen content within the circumpolar current might confirm this conclusion. From the Meteor observations (in 1926) Wüst finds in the Weddell Sea region an oxygen content of 4.6 ml/L at a temperature of 1°6, and of 5.6 ml/L at a temperature of -0°6. The oxygen observations on the Australian Antarctic expedition and L. Christensen's expedition with Thorshavn, and observations from the Drake Passage on board Discovery II in 1931 indicate a decrease of the oxygen content of the deep water from the region north of the Weddell Sea and eastward to Drake Passage. Within the Antarctic circumpolar water, the oxygen content increases toward the bottom and the temperature decreases. Thus, a relation exists between the oxygen content and the temperature and, on an average, the oxygen content is nearly a linear function of the temperature.

In the Weddell Sea region (1926)
$$O_2 = [4.42 + 0.45(2° - t)] ml/L$$
In the Indian Antarctic Ocean (1929-1930)
$$O_2 = [4.18 + 0.50(2° - t)] ml/L$$
In the Drake Passage (1931)
$$O_2 = [3.95 + 0.45(2° - t)] ml/L$$

The Meteor observations in the Drake Passage in 1926, however, show very nearly the same oxygen content as the water of similar temperature and salinity to the north of the Weddell Sea.

Drake Passage (1926) $O_2 = [4.35 + 0.45(2° - t)] ml/L$

Thus, the evidence is conflicting and at present it can only be stated that a majority of observations indicate a decrease of the oxygen content of the deep water in an

eastward direction from the Weddell Sea to the Drake Passage, as would be expected if the flow is directed to the east, but this feature needs to be confirmed. It may be added that great variations may occur, owing to variations in the admixture of water from the shelf, and such variations may be responsible for the different conditions in different years.

The deep water of the Pacific is, as already stated, similar to the deep water of the Antarctic circumpolar current, which is characterized by temperature between 0° and 2°, and by salinity between 34.68 and 34.74 per mille. From table 9 it is seen that below 3000 meters the temperature lies between 1°.2 and 1°.9, if we disregard Region 6 off Central America. The observed salinity lies between the limits 34.62 and 34.68 per mille, but the values are probably consistently about 0.03 per mille too low, and the actual range is therefore 34.65 to 34.71 per mille, in good agreement with the salinity of the circumpolar waters. The highest salinities (corrected values greater than 34.7) are found in the South Pacific where, according to the few available data, the oxygen content of the deep water appears to be relatively high. These features indicate that the deep water of the South Pacific is slowly renewed by addition of water from the circumpolar current. Whether this renewal has the character of the regular inflow in some definite region or takes place by irregular processes of mixture cannot be decided by means of the available data.

In the North Pacific the salinity of the deep water is slightly lower, and the oxygen content considerably lower. These features indicate that the renewal of the deep water of the North Pacific by admixture of water from the Antarctic region is much slower than in the South Pacific, and, furthermore, it must be assumed that slow admixture of intermediate water of low salinity takes place and reduces the salt content of the deep water.

The information which is now available strongly points in the direction that no definite flow of deep water exists in the Pacific Ocean and that the renewal of the water is a result of slow and irregular processes of mixing. It cannot be doubted, however, that on an average a transport of deep water takes place from south to north. It is possible that this transport takes place principally along the bottom, and that an outflow of deep water from the Pacific is present at some high level. It is also possible that the outflow from the Pacific takes place within the upper layers and that slow descending motion of the deep water occurs in certain regions.

Currents

Surface Currents

On several occasions we have touched on the problem of the circulation of the waters in the Pacific and especially have discussed to some extent the intermediate currents in the South and the North Pacific. We shall now undertake a more detailed discussion of the circulation as far as this is possible by means of the Carnegie data. The discussion will be based principally on the charts showing the topography of the isobaric surfaces 0, 100, 200, 300, 400, 500, 700, 1000, and 1500 decibars relative to the topography of the 2000-decibar surface. In these charts, lines of equal relative elevation have been drawn, except off the coast of Japan where the conditions are too complicated to be represented by the few observations of the Carnegie in this region.   Near the

equator the course of the lines is also very doubtful for reasons which will be explained when dealing with the Equatorial Countercurrent.

The charts represent very nearly the absolute topography of the different isobaric surfaces because it can be assumed, on account of the uniform character of the deep water, that the 2000-decibar surface is very nearly horizontal. It must be borne in mind, however, that when constructing the charts we combined the data from stations which in some regions were taken at great intervals of time. This combination may lead to apparent irregularities, especially in regions where the current systems undergo considerable displacement. Furthermore, it must be emphasized that from our representations we can draw conclusions only as to the currents which are maintained by the distribution of density. The distribution of density is partly maintained by the processes of heating and cooling, evaporation and precipitation, and partly by the effect of the prevailing winds on the surface layers.

It is clear that differences in heating and cooling in the different latitudes, and differences in evaporation and precipitation, create differences in density which maintain a system of currents independently of the action of external forces such as the tangential force exerted by the prevailing wind. On the other hand, it is not self-evident that the prevailing winds influence the distribution of density in such a manner that part of the effect of the winds is included in the currents which are computed on the basis of the distribution of density, but some evidence that such is the case can be found.

Figure 22 shows the currents at the surface, supposing the water at a depth of about 2000 meters to be at rest, and supposing that the velocity, v, of the currents can be derived from the map representing the topography of the surface by means of the formula

$$v = (1/L)(c/\sin \phi)$$

where L is the distance between two lines of equal dynamic height (anomaly), and ϕ is the geographic latitude, and c is a constant. The current is directed at right angles to the gradient of the isobaric surface, that is, parallel to the lines of equal dynamic height.   In the Northern Hemisphere it is directed 90° to the right of the gradient, in the Southern Hemisphere 90° to the left.

This computation probably gives velocities which are too great in the vicinity of the equator because the friction, which is not considered, probably plays a greater part in this region. Aside from these restrictions the computed surface currents represent the currents which result from the distribution of density between the surface and a depth of about 2000 meters.

This map of the surface currents will now be compared with the map of the surface currents (figure 23) constructed by Merz and published by Wüst (1929). The latter map is based on the observed surface currents as obtained by dead reckoning and astronomic observations on board ship, and thus represents the actual currents as resulting from the combined effect of the prevailing winds and the distribution of density. The agreement between the two maps is remarkable, considering the widely differing material on which they are based. Some discrepancies are found in the northern part of the North Pacific, but it may be noted that:

1. The line separating the easterly and westerly currents in the North Pacific in figure 22 lies near the line of subtropic convergence as shown by Merz.

2. The convergence in latitude about 40° north off the coast of Japan in the figure corresponds to the western part of the northern polar front as shown by Merz.

3. The westerly current in the inner part of the Gulf of Alaska is seen in both maps.

4. The Equatorial Countercurrent runs in nearly the same regions on the two maps.

5. The line separating the westerly and easterly currents in the eastern part of the South Pacific practically coincides with the corresponding line of subtropic convergence as shown by Merz.

It is hardly a coincidence that the surface currents, which are derived from dynamic computations, agree with the observed surface currents, in spite of the fact that the latter result from the combined effect of the wind and the primary distribution of density. This agreement must be interpreted as indicating that the effect of the wind is to maintain a certain distribution of density, and the computation of the currents on the basis of the density distribution actually includes part of the effect of the prevailing winds.

Palmén (1930) has recently discussed a number of observations from the Gulf of Bothnia which demonstrate in a striking way the effect of the wind on the distribution of density. When the wind blows in the direction of the Gulf the light water is accumulated along the right-hand shore and the heavy water along the left-hand shore. The current, which is computed from this distribution of density (the convection current according to Ekman's terminology) has a velocity corresponding to the velocity of the wind current which would be produced under the given circumstances. This example deals with conditions in a narrow bay, but it is probable that the results are of general importance and that even in the open ocean we may find that the wind changes the distribution of density in a corresponding manner. This would mean that a prevailing wind maintains an abnormal distribution of density. If the wind should stop blowing, the normal distribution of density would be re-established, and the dynamic computation would give the current which would be present if the tangential force exerted by the wind on the surface were absent. Supposing these considerations to be correct, we may regard our dynamic charts as representing the total currents resulting from the differences in density which would occur in the absence of wind, and from the abnormal distribution of density which is established and maintained by the action of the wind.

As to the character of the wind current we remind the reader of Ekman's theory. According to this the total transport of water is directed 90° to the right of the direction of the wind in the Northern Hemisphere, and 90° to the left in the Southern Hemisphere. The depth to which the wind current reaches depends on the latitude and on the eddy viscosity, which again is a function of the stratification of the water.

In general, it is assumed that at some distance from the equator the wind currents reach to less than 100 meters in depth, but the effect on the distribution of density must reach much deeper. Since the surface water is light, a transport of surface water to the right of the direction of the wind leads to an accumulation of light water on the right-hand side of the wind, and on the left-hand side the light surface water must be replaced by heavier water from greater depths. On the right-hand side of the wind the surfaces of equal density are depressed, and on the left-hand side they are raised. The effect may reach to considerable depths and, owing to this "abnormal" distribution of density, a current in the direction of the wind is created.

In the open ocean the maintenance of an abnormal distribution of density represents only part of the effect of the wind. If it represented the total effect, the condition

$$(\nu \frac{dv_x'}{dz})_0 = -T_x, \quad (\nu \frac{dv_y'}{dz})_0 = -T_y$$

would have to be fulfilled. Here ν is the coefficient of eddy viscosity, v_x' and v_y', the components of the convection current, and T_x and T_y, the components of the tangential stress of the wind. This condition, which may be satisfied in a narrow channel, is never fulfilled in the open ocean, since a decrease of the required magnitudes of the velocity near the surface does not occur. Pure drift currents will, therefore, be present beside the convection current, but under stationary conditions the climatological factors may balance their effect on the distribution of density. We shall not enter any further on this subject but shall, in the following, consider only the currents which are associated with the distribution of density.

We shall first examine the currents in the troposphere, which extend to a depth of about 500 meters. In the North Pacific the dominant feature is represented by the anticyclonic current system which has its center in latitudes 25° to 30° north, and in longitude about 180°. It is perhaps not correct, however, to use the term "center" because, apparently, we find an axis of maximum elevation of the isobaric surfaces stretching from the region to the south of Japan toward the Hawaiian Islands. On the northern side of this axis we find currents toward the east, and on the southern side currents toward the west or southwest.

A similar current system is probably present on the Southern Hemisphere, but our observations are not extended over a sufficiently wide area to disclose the different branches of this system. In our charts we find the westerly current represented between latitudes 0° and 20° south, although it appears to have a less stable character than the corresponding current in the Northern Hemisphere. The easterly current is seen to the south of latitude 30° south between longitudes 80° and 120° west. Between the tropical westerly currents we find the Equatorial Countercurrent which is in longitude 140° north and latitude 11° north where it runs as a very strong and narrow current, and in longitude 175° west appears as a rather broad and weak current extending to both sides of the equator, but to the greatest distance on the northern side.

It is of advantage to discuss separately the different branches of the current systems in the two hemispheres and we shall, as previously, begin with the most southern part of the South Pacific.

In the southeastern part of the Pacific our charts show the northern branch of the South Pacific east drift. The current runs toward the east between latitudes 30° and 40° south, and can be followed from the surface to a depth of 500 meters, but the velocity decreases downward and is very small below 300 meters. Above a depth of 400 meters the current appears to turn toward the west in latitude 30° south, but below 400 meters a closed circulation appears to be present between longitudes 80° and 120° west.

The greater part of the water masses which are carried to the east does not turn toward the equator until reaching the South American coast, then it follows this coast toward the north as the Peruvian Current. This current can be traced to a depth below 500 meters. We have previously pointed out that water of low temperature is found at a short distance from the surface off the coast of Peru, and that the surface temperatures are very low in this region. It cannot be doubted that these low surface temperatures are owing to a vertical movement which carries water of low temperature to the surface, but the accumulation of cold water off the coast can be explained without taking a possible vertical movement into consideration. We must bear in mind that water is transported toward the coast of South America by the predominating current toward the east. This water is forced to change its course and to continue toward the equator. The Peruvian Current is, thus, a "forced" current which must exist because of the land boundaries of the ocean. In such a current we must find the normal distribution of density, which means that in the Southern Hemisphere we must find water of high density on the right-hand side of the current and water of low density on the left-hand side. Consequently the density must increase toward the coast or, if the salinity is nearly constant, water of low temperature must accumulate along the coast. The accumulation of cold water along the coast of South American gives, therefore, no evidence of an upwelling motion which reaches to great depths, but indicates only that a current follows the coast toward the equator (cf. Helland-Hansen [1912]). On the other hand it is evident because of the conspicuously low surface temperatures, that water from moderate depths is drawn to the surface at the coast. This upwelling from moderate depths is probably maintained by prevailing winds and is a secondary effect as compared with the large accumulation of cold water at greater depths. The actual surface current, which represents the combined effect of the distribution of density and of the wind, probably is directed away from the coast, for which reason the continuity would necessitate a supply of water from below, that is, an upwelling.

As to the direction of the winds which maintain the offshore currents, it should be borne in mind that on account of the effect of the rotation of the earth, the transport of water by wind takes place at right angles to the direction of the wind, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The winds, therefore, which approximately parallel the coast toward the equator, give rise to a transport of water having an offshore component.

It is well known that the regions of upwelling are all found at the west coasts of the continents where the wind currents transport water away from the land. The upwelling has, therefore, generally been attributed to the effect of the winds. The present interpretation of the observed conditions does not differ from the accepted explanation of the upwelling, but here it is emphasized that the upwelling water comes from small depths and that the the accumulation of cold water in greater depths is not a result of the upwelling but is associated with the presence of a "forced" current along the coast.

To the north of latitude 20° south we find, on the whole, currents which are directed toward the west. Here we have the region of the westerly tropical current in the South Pacific. This westerly current appears to be very irregular. In the region from the coast of Peru

to longitude 120° west it appears as if divergent currents are found to a depth of about 100 meters. These diverging currents may be an effect of the prevailing east winds which carry the surface water to the north on the northern side of the equator and to the south on the southern side. If this is correct, we must assume that ascending motion takes place in the region to the south and the west of the Galapagos Islands, and such currents would account for the low surface temperature of this region. The high phosphate content of the surface water in this region supports such a conception. Below a depth of 200 meters water from the northwest appears to flow toward this region, perhaps compensating for the water which is drawn to the surface. Farther west, between longitudes 120° and 170° west, we find that the currents have considerable components from the south down to a depth of about 200 meters. In this region, at a depth of between 100 and 200 meters, the southern part of Section V indicates a considerable northward flow of water of high salinity. The dynamic charts confirm that such a flow takes place above the 200-meter level because the northerly component of the current is greatest down to this level. The irregularities in the topography of the isobaric surfaces perhaps indicate that the flow toward the equator of water of high salinity does not take place continuously but has an intermittent character. The fact that the irregularities are especially present above the 200-meter level points in this direction. An intermittent transport of water toward the equator means that whirls develop within which subsurface water may be transported to the surface. At several stations in this this region water of high phosphate content and low oxygen content is found, indicating that such transport takes place.

Before concluding the discussion of the westerly tropical current, we shall emphasize that this current, aside from the wind current at the surface, dynamically is partly of the same character as the Peruvian Current. The water, which is transported toward the South American coast by the easterly current in the South Pacific and is forced toward the equator along the continent, cannot sink because of its low density and must return toward the west as a surface current within which the easterly winds carry the light water to the south. The westerly tropical current is thus in part maintained by the same forces which maintain the easterly current in the southern part of the ocean and in part by the prevailing winds. In the Southern Hemisphere we find water of low density on the left-hand side of the current and water of high density on the right-hand side; that is, an accumulation of heavy water under the equator and an accumulation of light water to the south of the westerly current. This distribution of density must be regarded as a "forced" distribution owing to the limitation of the ocean in an east and west direction and to the effect of the prevailing winds.

To the north of the equator a corresponding current is found, the westerly tropical current of the North Pacific. Observations are lacking for a great part of the North Pacific between the coast of Central America and longitude 130° west and our picture, therefore, is incomplete. It appears, nevertheless, as if the form of the North American Continent is of considerable importance to the development of the currents. We shall deal further with this subject when discussing the California Current.

The westerly tropical current in the North Pacific

appears to be stronger and more regularly developed than the corresponding current in the Southern Hemisphere. The former current must also be regarded as a forced current which is maintained partly by the prevailing winds and partly by the factors driving the easterly current of the northern part of the ocean, namely, the differences in density between the subtropical and the subarctic water. Since the North Pacific is limited on the north, the entire mass of water which is carried toward the east in the North Pacific must return, whereas in the South Pacific a considerable part of the water continues eastward to the south of South America. This circumstance perhaps explains the more conspicuous development of the westerly tropical current in the North Pacific.

Off the coast of Japan, in the latitude of Yokohama and to the north of this latitude, we find very complicated currents. No lines have been drawn, but by means of the numerical values on the chart, one easily recognizes the line of demarcation, representing the boundary between the warm water to the south and the cold water to the north, which was seen in Section IX. A warm current, the Kuroshio, can be traced as a narrow and very strong current which follows the southeast coast of Japan to approximately latitude 37° north. Here it meets the cold current coming from the northeast, the Kurile (Oyashio) Current. Both currents bend toward the east, the Kuroshio partly to the south and the Kurile Current partly to the north. Along the border of the two currents a succession of whirls is apparently developed and it is probable that future observations will show that these whirls develop at various places along the line of demarcation and reach varying intensities. The observations of the Carnegie indicate the major features of the current system but cannot be used for a discussion of the details. We remind the reader that a corresponding region with great contrasts is found in the North Atlantic to the south of the Grand Banks, and that corresponding whirls undoubtedly are developed there.

The whole of the North Pacific to the north of latitude 30° north is dominated by the easterly current, which in the southern part carries warm water of high salinity, and in the northern part carries cold water of low salinity. Because of the difference in temperature, the density is increasing toward the north. The observations of the Carnegie cannot disclose any details as to this current, but they show that it is strongly developed to a depth of more than 500 meters. The inclination of the isobaric surfaces toward the north in the North Pacific is the dominating feature in the topography of the surfaces.

The easterly current of the North Pacific divides into two branches when it strikes the coast of North America. The northern branch turns toward the north and bends into the Gulf of Alaska and returns toward the west on the southern side of the Aleutian Islands. This branch is shown in the British Admiralty Charts and in the chart by Merz, and appears in our charts, thanks to the observations made in the Gulf of Alaska by the United States Bureau of Fisheries.

The other and more important branch of the easterly current of the North Pacific bends toward the south. The form of the North American coast is probably of great importance to the turning of the current, and to the fact that the southerly current along the coast runs with a very high velocity off the coast of California where it is known as the California Current. As in the case of the Peruvian Current, the increase of density toward the coast cannot be ascribed to an upwelling of deep water, but is dynamically conditioned. The California Current, as it appears on our dynamic maps, is maintained by the difference of density between the subtropical and subarctic regions, but the increase in density toward the coast is a direct result of the existence of the current.

An upwelling takes place in the upper layers because of the transport of water away from the shore by prevailing winds. Thorade (1909) has shown that this transport and, consequently, the upwelling is subjected to considerable seasonal change. As to the character of the upwelling and the relation of this phenomenon to the low temperatures at greater depths, we refer to our discussion of the Peruvian Current. In this place it should again be emphasized that according to our conception the low surface temperatures are the result of an upwelling of water from small depths, whereas the low temperatures at greater depths have nothing to do with the upwelling, but are associated with the presence of a southerly current along the coast.

The rapid heating of the surface, which takes place in this southerly latitude, must lead to the development of a thin surface layer of relatively high temperature. The transition from this surface layer to the underlying water takes place in a short distance, and convective currents therefore cannot penetrate to any great depth. The velocity of the California Current decreases with increasing depth and at a depth of 400 meters the current is very weak.

In the regions between the coast of California and the Hawaiian Islands the currents are rather irregular. At the most northern stations we find, on the whole, an easterly current and at the most southern stations a westerly current, and between the Islands and the American coast the water flows mainly from the north. From the appearance of sections VII and XV, and from the curves showing the vertical distribution of temperature and salinity at stations 139 to 146, it appears as if a transport of water toward the north takes place in the upper layers at stations 142 to 146. The dynamic charts do not indicate such a transport, which perhaps must be attributed to the effect of the wind. Below a level of 200 or 300 meters the transport appears to take place principally from the west.

At the stations in the immediate vicinity of the Hawaiian Islands we find a rather strong surface current from the east which, however, decreases rapidly in velocity with increasing depth. The water of high salinity, which is found below the surface at stations 139 and 140, appears to come from the region of high salinity to the west.

The Equatorial Countercurrent is especially well developed in the Pacific. As a rule it is a little to the north of the equator, running with high velocity toward the east. It is probable that this current is extended across the whole width of the Pacific Ocean but it is undoubtedly subjected to considerable variations, partly of seasonal character and partly owing to circumstances of which we have no knowledge. It is generally assumed (Defant, 1928; Krümmel, 1911) that the Equatorial Countercurrent represents a compensation current carrying back again to the east part of the water which is transported toward the west by the trade-wind currents. Furthermore, it is assumed that this countercurrent,

which is known to be a narrow current on the surface, widens with depth. The latter conception, as to the increasing width of the Equatorial Countercurrent, cannot be upheld according to the Carnegie results; on the contrary, the current is typical of the upper layers only, and since it has a very limited extension it must be doubted that this flow of water represents a compensation action. It will be shown on the basis of the Carnegie data that the countercurrent probably is owing to the asymmetric development of the westerly tropical currents of the two hemispheres and to the effect of diverging surface currents in the vicinity of the equator.

Before turning to the observations of the Carnegie a few general considerations are necessary. Attention should be drawn to the fact that the inclination of the isobaric surfaces must change when passing the equator because of the change of the direction of the deflecting force of the earth's rotation. In other words, the isobaric surfaces must have a maximum or a minimum at the equator. If the isobaric surfaces had a definite inclination at the equator, the direction of the current would change by $180°$ when passing the equator and such a condition cannot be stable.

If the isobaric surfaces show a maximum at the equator, the surfaces are inclined to the north in the Northern Hemisphere and to the south in the Southern Hemisphere, and the current is directed toward the east on both sides. If, on the other hand, the isobaric surfaces have a minimum at the equator the current is directed toward the west.

We have seen previously that the westerly tropical currents in both hemispheres must be regarded as forced currents, which are maintained partly by the prevailing winds and partly by the density currents in the northern and southern parts of the ocean. Within these westerly tropical currents in the Northern Hemisphere we must have the heavy water to the left, which means near the equator, and in the Southern Hemisphere the heavy water must lie to the right, which also means near the equator. Therefore, since these forced currents toward the west exist, we must find an accumulation of heavy water in the vicinity of the equator. Assuming, for for the sake of simplicity, that we have two layers only, one light on top and one heavy below, the conditions have been represented schematically in figure 24a, in which the boundary surface between the two water masses shows an upheaval under the equator. Assuming the isobaric surfaces in the heavy water to be horizontal, the isobaric surfaces must have the courses which are indicated by means of the thin lines. In this case the topography of the isobaric surfaces shows a minimum at the equator, and within the light water, we find a current toward the west on both sides of the equator, whereas the heavy water is at rest. No countercurrent exists.

If, however, for some reason the accumulation of heavy water is asymmetric when referred to the equator, a different system is developed. The conditions which are shown in figure 24b cannot exist. We cannot find a single upheaval of the heavy water on one side of the equator because this would give the isobaric surfaces an inclination at the equator. Considering that the isobaric surfaces must have a maximum or a minimum at the equator, two types of asymmetric development are possible, as shown in figures 24c and 24d. In figure 24c we have a small upheaval of the heavy water under the equator and a big upheaval to the north. When such a distribution of density is present, the isobaric surfaces show

two minima, one at the equator and one to the north of the equator. These two minima are separated by a maximum and the water in the region between this maximum and the northern deep minimum must flow to the east. That means that here we find a countercurrent which, however, is present in the upper light water only. The light water reaches to greater depths to the north and to the south of the minima and the westerly current is, therefore, deeper than the countercurrent. In the second case, figure 24d, we find accumulations of heavy water on both sides of the equator but the accumulation on the northern side is the greater. The isobaric surfaces show a maximum at the equator and minima on both sides, and between the two minima a countercurrent flows toward the east. The case in which the two upheavals of the heavy water are equally developed is probably of minor interest because then symmetry exists as to the equator and the simpler system in figure 24a seems more probable. The greatest upheaval may, of course, be found in the Southern Hemisphere, but this cannot lead to any principal differences.

From these considerations it seems probable that an asymmetric development of the westerly tropical currents may give rise to an asymmetric accumulation of heavy water near the equator, and that the dynamic system which then is established leads to the countercurrent toward the east between the two westerly currents. The width of the countercurrent and the one-sided development in reference to the equator depends on the character of the asymmetry, but the countercurrent must in all cases be regarded as a dynamically conditioned current.[1]

We have the possibility of discussing the equatorial currents for two occasions when the Carnegie crossed the equator. The sections were both taken in directions which form angles less than $90°$ with the equator, but, for the sake of simplicity, we shall plot the values as if they were taken along two meridians; that is, we shall plot the stations at the observed latitudes and disregard the differences in longitude between the stations. The eastern section is taken nearly in the central part of the Pacific along the average meridian of $145°$ west, whereas the western section is taken in the western half of the Pacific approximately along the meridian of $180°$.

In order to study these sections we have computed the distances in dynamic meters between the isobaric surface of 700 decibars and the isobaric surfaces 0, 50, 100, 150, 200, 250, and 300 decibars. We have selected the isobaric surface of 700 decibars as the reference surface because this surface is practically parallel to the surface of 2000 meters. Also, accidental errors of observation exercise a greater influence at depths below 700 meters since the intervals between the observations there are greater. Assuming the isobaric surface of 700 decibars to be horizontal, we have constructed

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[1]Later on the author (1939) has pointed out that the observed distribution of mass does not given any clue to the understanding of the dynamics of the countercurrent. The dynamics have recently been discussed by Montgomery (1940) and by Montgomery and Palmén (1940). They state that the trade winds by continually exerting a westward stress on the sea surface produce a westward ascent of the sea level in the equatorial region. The equatorial countercurrents are found in the doldrums and apparently result as a down slope flowing in this zone where the winds maintaining the slope are absent.

profiles of the isobaric surfaces down to the surface of 300 decibars. Furthermore, we have represented the distribution of density, salinity, and temperature by means of vertical sections which are extended to a depth of 300 meters, and in the case of the central section we have also represented the amount of oxygen, but from the western section no observations of oxygen are available.

The profiles of the isobaric surfaces of the central section are represented in figure 25. As in the other vertical sections, north is to the right and south is to the left. These profiles are of the type shown schematically in figure 24c. When drawing them, one has a certain freedom because of the considerable distances between the stations, but a minimum must be placed somewhere near the equator, and then it is permissible to place it at the equator where it theoretically should be.

It is seen on the figures that currents toward the west are dominating. At the surface they are found to the north of latitude 10° north and to the south of latitude 03° 40′ north. Currents in the opposite direction, toward the east, are at the surface between the two latitudes 10° and 7° 30′ north. Within these latitudes the Equatorial Countercurrent is fully developed. The most interesting feature shown by the profiles is that the velocity of the countercurrent decreases very rapidly with increasing depth. At a level of 100 meters it is already much weaker than at the surface, and at a level of 200 meters it has practically disappeared. The westerly current also decreases with increasing depth, especially near the equator, but in latitudes 20° north and 10° south a considerable current toward the west still exists at 300 meters. These observations show that the Equatorial Countercurrent does not widen with depth but, on the contrary, becomes narrower and narrower, and disappears above a level of 200 meters.

Turning next to the western section, figure 30, we find essentially the same features but here the profiles of the isobaric surfaces are of the type shown in figure 24d. In this case, a maximum must be placed somewhere near the equator, and it is permissible to place it at the equator, in agreement with the theoretical conditions.

The currents toward the west are also dominating here, extending to the north of latitude 6° 20′ north and to the south of latitude 3° 20′ south. Between latitudes 6° 20′ north and 3° 20′ south the current runs in the opposite direction, toward the east. In this case we find a maximum elevation of the isobaric surfaces at the equator. The Equatorial Countercurrent is thus extended over a broad area on both sides of the equator. It has its maximum velocity somewhat below the surface at a level of about 100 meters but from this level the velocity decreases rapidly with increasing depth until the current practically disappears at 300 meters. The currents toward the west also decrease with increasing depth, especially at the shortest distance from the equator as was the case in the preceding section. The two sections give us essentially the same results. The different position and development of the countercurrent may perhaps be explained by the fact that the western section was taken in April, at the beginning of the northern summer, whereas the central section was taken in November, at the beginning of the southern summer, but it also may be related to the different geographic locations.

The different development of the countercurrent at

the two crossings of the equator makes it impossible to combine the observations to form a consistent picture of the topography of the isobaric surfaces in the vicinity of the equator. There the lines of equal elevation in the charts, therefore, have no physical significance.

The density sections, figures 26 and 31, give the same picture in both cases. We find accumulations of heavy water under the northern and southern borders of the countercurrent, whereas lighter water extends to greater depths within the countercurrent itself. In the central section the upheaval of the cold water is especially characteristic at the northern border of the countercurrent.

Turning to the salinity, temperature, and oxygen sections, figures 27, 28, and 29 from the central region, we obtain some information as to the character of the vertical motion. From the salinity sections it is evident that we find ascending motion along the borders of the westerly currents. The ascending motion is especially strong on the northern side of the countercurrent, where water of low salinity is brought practically to the surface. The course of the isohalines indicates that the surface water is driven away from the countercurrent both on the northern and the southern sides, and the salinity section, therefore, supports the opinion that diverging surface currents are present and are of importance to the development of the system. The temperature section discloses the same features as the salinity sections. It shows especially the upward movement on both sides of the countercurrent and, in addition, a downward movement at the southern boundary.

The oxygen section, figure 29, shows some very interesting features. The axis of the lowest salinity values in the salinity section follows exactly the line of 4 ml/L. The ascending water on the northern side has thus, on the whole, an oxygen content above 4 ml/L. On the southern side we find that the ascending water has a somewhat lower oxygen content, namely, 3 ml/L. The descending movement at the southern boundary of the countercurrent can hardly reach to any considerable depth because even in the central part we find a rapid decrease of the oxygen content below a level of 150 meters.

A very rapid change of density with depth is found at a short distance below the surface at the stations where the heavy deep water reaches almost to the surface, and where the stable stratification prevents mixing between surface water and the deep water. The deep water, which rises as a wedge at the northern border of the countercurrent, is without any communication with the surface water and consequently we find that this deep water is practically without oxygen. Values as low as 0.03 ml/L were observed in this region and values below 0.25 ml/L occur within an extensive mass of water. The contrasts are smaller on the southern side of the countercurrent where the density changes more gradually with depth, and where a slow mixing between the surface waters and the deep waters may take place.

The western temperature and salinity sections show several features which are similar to those of the central regions, but the contrasts are less conspicuous and the indications of vertical movement are less definite. From the salinity section it is evident that ascending motion takes place along the borders of the westerly currents, especially on the northern side of the countercurrent.

The conditions which are revealed by the observations

of the <u>Carnegie</u> are in close agreement with our general considerations. On both sides of the equator we find westerly currents reaching to considerable depths and there separated by heavy water which is practically at rest. Between the westerly currents the countercurrent is embedded as a swift but shallow current. The heavy water at rest reaches nearest the surface at the northern and southern boundaries of the countercurrent.

Intermediate Currents

We have already discussed the origin of the intermediate water of low salinity in the Southern Hemisphere and have shown that this water probably sinks at the Antarctic convergence. When studying the sections we found the axis of the intermediate current at a depth of 600 to 700 meters within the areas from which observations are available. These areas are so limited, however, that we cannot follow the flow of the intermediate current and our dynamic charts give only some hints as to the character of this current. From the dynamic charts for the levels 500, 700, and 1000 meters it looks as if the circulation of the intermediate current takes place in a clockwise direction, contrary to the tropospheric circulation which is counterclockwise. This result needs confirmation, but what seems certain is that the flow of the water takes place principally in an east and west direction and that the north and south component of the current is very weak in the central part of the South Pacific. The flow of water, which at the 700-meter level is directed away from the coast of South America, perhaps transports back again part of the water which is carried toward the coast by the currents of the troposphere. The westerly current off the coast at a depth of 700 meters should then be regarded as a compensation current.

In the Northern Hemisphere the circulation of the intermediate water takes place in the same direction as the circulation within the troposphere and is in both cases clockwise. We have seen that the intermediate water probably is formed in the eddies which develop off the coast of Japan at the boundary between the warm current from the southwest and the cold current from the northeast. Water of a salinity between 33.09 and 34.00 per mille and of a temperature of about 5°, which is formed in this region, is transported toward the east, turns toward the south when approaching the American coast, and returns toward the west in approximately latitude 20° north. On this journey both the temperature and the salinity of the water increase because of the processes of mixing. The water, therefore, has a higher temperature and a higher salinity when it bends toward the north on the west side of the ocean after having completed one circuit, than it had when beginning the circuit. When carried toward the north it is mixed with water of lower temperature and lower salinity coming from the north, and new water of the typical properties of the intermediate layer is again formed. This new water compensates for the loss which has taken place because of the processes of mixing, and because a transport of intermediate water toward the equator probably exists, as was shown when dealing with the Equatorial Countercurrent.

The intermediate current in the Northern Hemisphere is, on the whole, a subsurface current, in contrast with the corresponding current in the Southern Hemisphere which originates at the surface. The difference in the oxygen content of the intermediate water supports this conception (see p. 50).

Velocity of Currents between the Surface and 700 Meters

Up to this point the discussion of the currents has been based on the topography of the isobaric surfaces, and the currents have been treated qualitatively only. Current charts 0 to 700 meters (figs. 34 to 38) show direction and velocity of the currents, as computed from the inclination of the isobaric surfaces, supposing that the conditions are stationary, and that the motion is frictionless and negligible at the 2000-decibar surface. It must again be emphasized that the values in the figures are obtained by combining observations, which in several regions were made at great intervals of time. This combination may lead to apparent irregularities, especially in regions where the currents undergo considerable displacement. Also in the vicinity of the equator the computed velocities are uncertain because of the topography of the isobaric surfaces and because there the friction may play a greater part than elsewhere. In spite of these reservations, however, it is probable that the charts show the approximate order of magnitude of the currents which are maintained by the distribution of density.

In the Southern Hemisphere the <u>easterly current</u> of the South Pacific shows velocities which, at the surface, vary from 2 to 9 cm/sec, increase to a depth of 100 meters where they reach 12 cm/sec, and decrease rapidly below 100 meters. At 400 meters the eastward velocities are only 3 cm/sec or less, and at 700 meters the direction is reversed, the water flowing toward the west with a velocity of 1 to 2 cm/sec. The Peruvian Current appears to be a very weak current. At the surface the velocities range from 2 to 5 cm/sec and decrease downward to about 2 cm/sec at 700 meters.

Within the westerly tropical current of the South Pacific we find surface velocities up to 30 cm/sec, 14 nautical miles in 24 hours. Still greater velocities are met with at 100 meters, but below this level the velocities decrease rapidly and at 700 meters no distinct motion toward the west is perceptible. The irregular character of the westerly tropical current of the Southern Hemisphere is clearly evident from the figures.

In the northern Hemisphere the westerly tropical current shows the greatest velocities near the surface, where they approach 30 cm/sec. The velocities decrease with increasing depth, and at the same time the current is being displaced toward the north. At 700 meters the velocities are less than 2 cm/sec.

At the surface, in longitude 140° west, the Equatorial Countercurrent has a velocity of about 50 cm/sec, or nearly 24 nautical miles in 24 hours. This value is again very probable. At greater depths the countercurrent disappears, and the crosscurrents, which are shown at 700 meters, probably have no real significance.

The warm current along the coast of Japan, the Kuroshio, is not represented in the figures, but the cold Kurile Current (Oyashio) is seen at all levels. The velocity of this current decreases from 17 cm/sec at the surface to about 2 cm/sec at 700 meters. The changes in the direction of the current with depth are perhaps associated with the presence of whirls.

The easterly current in the northern part of the North Pacific can be traced at all levels. The velocities decrease with increasing depth, from 2 to 9 cm/sec at

the surface and 100 meters to 0.8 - 3 cm/sec at 700 meters.

The westerly current in the Gulf of Alaska has a velocity of 7 cm/sec at the surface, but at 400 meters it has practically disappeared. The southerly current along the coast of California shows a velocity of 17 cm/sec at the surface. This velocity also decreases downward, but below 400 meters the decrease appears to be very small because at the levels 400 and 700 meters the computed velocities are 4.3 and 4.2 cm/sec respectively.

The numerical values which are shown in the figures and briefly treated here give, no doubt, a fairly correct idea of the intensity of the circulation in the Pacific, especially in the North Pacific, down to a depth of 700 meters, but the picture will probably be much modified in details when more observations become available.

Flow of the Deep Water

Since high temperatures are found in the equatorial regions, it is probable that a slow descending motion takes place here and that the circulation is to some extent, therefore, as suggested by Wüst (1930). The descending water, however, cannot contribute directly to the formation of the typical deep water because of its high temperature and low salinity, but must spread to the north and the south above the deep water.

In the North Pacific the bottom water and the deep water must come from the south because it cannot be formed anywhere in the area of the North Pacific. The inflow probably takes place near the bottom because there the highest oxygen values are found. The low temperatures in the northern part of the North Pacific at the levels below 2000 meters suggest an ascending motion of the deep water in this region. If this is correct, we must assume that the deep water returns to the south at a level between 2000 and 1000 meters, and on this journey it is being mixed with water from the intermediate current.

The deep water of the South Pacific must also come from the south and the greater part probably enters the Pacific to the south of New Zealand. Part of the deep water flowing into the South Pacific continues to the North Pacific, but another part probably ascends when approaching the equator and returns to the south at levels above 2000 meters. The distribution of oxygen leads to this suggestion.

It has already been indicated that at levels above 2000 to 1000 meters the water of the North Pacific probably moves to the south and thus flows into the South Pacific. At levels below 1000 meters the oxygen content, however, is much higher in the South Pacific than in the North Pacific, and this could not be the case if the water at these levels came from the North Pacific only. Therefore, in the South Pacific the return current above 2000 meters must carry water which mainly has been circulating in the South Pacific only, and with which some water from the North Pacific has been mixed.

It must be emphasized, however, that at any level the flow in an east-west direction is considerably stronger than the flow in a north-south direction. Because of this circumstance and of the obvious differences in the currents of the eastern and western parts of the ocean, no attempt has been made to give a schematic representation of the meridianal circulation in the Pacific Ocean. Such a representation would contain too many hypothetical elements, because at present it is not possible to arrive at any definite conclusions as to the flow of the deep water. Some possibilities have been suggested but these and others cannot be examined more closely before a greater number of observations are at hand.

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FIG. 1—SALINITY-TEMPERATURE RELATION, CENTRAL NORTH ATLANTIC OCEAN,
STATIONS 3, 5, 6, 15, 16, CARNEGIE RESULTS, 1928

SALINITY (PER MILLE)

TEMPERATURE (DEGREES CENTIGRADE)

POSITIONS OF STATIONS

STA-TION	LAT. NORTH ° ′	LONG. WEST ° ′
3	44 00	36 10
5	43 15	31 32
6	50 22	13 31
15	36 39	48 48
16	36 47	46 31

SLANT FIGURES DENOTE DEPTHS IN
HUNDREDS OF METERS
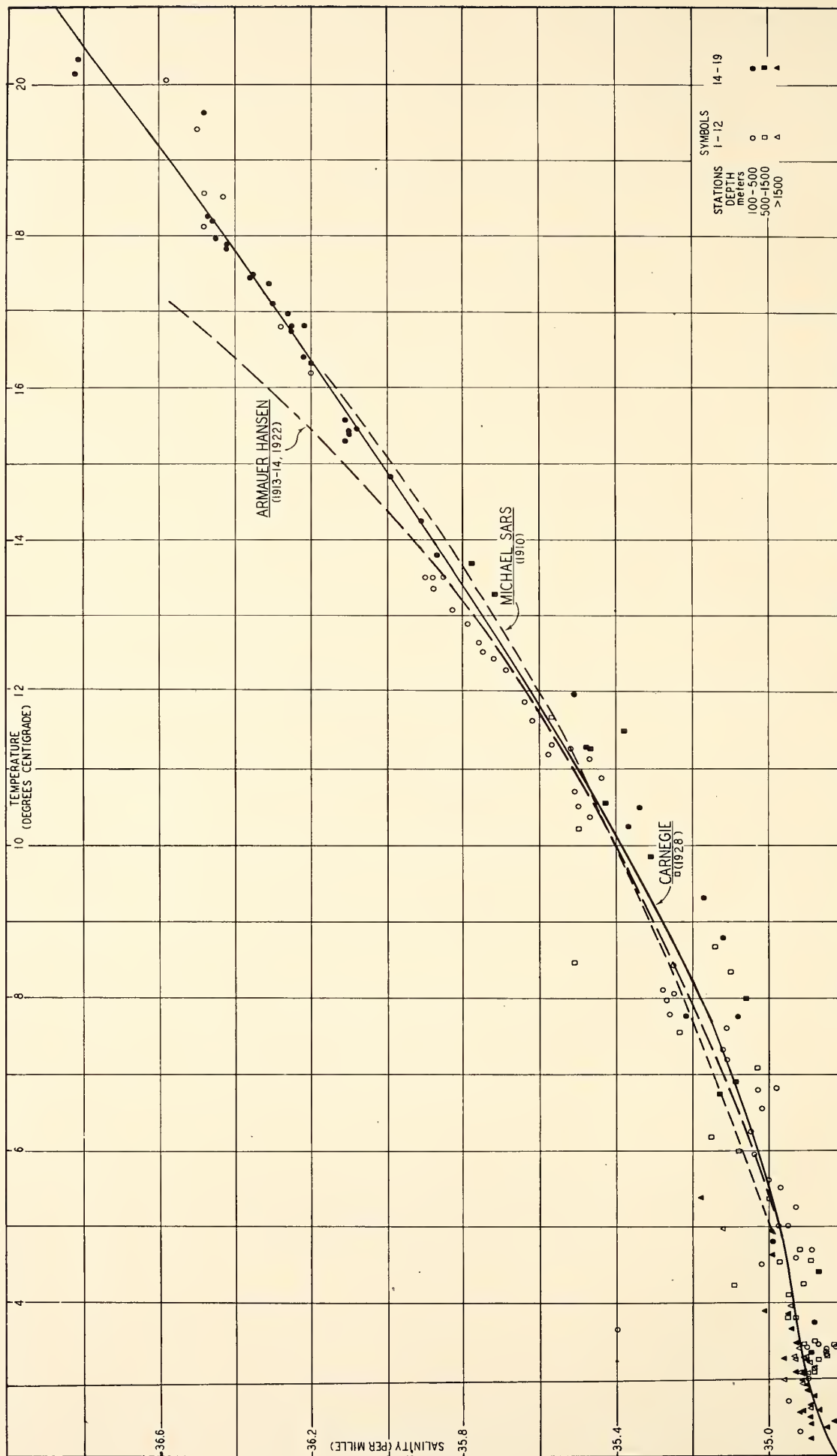
FIG. 2—TEMPERATURE-SALINITY RELATION, ATLANTIC OCEAN, FROM MICHAEL SARS, ARMAUER HANSEN, AND CARNEGIE RESULTS
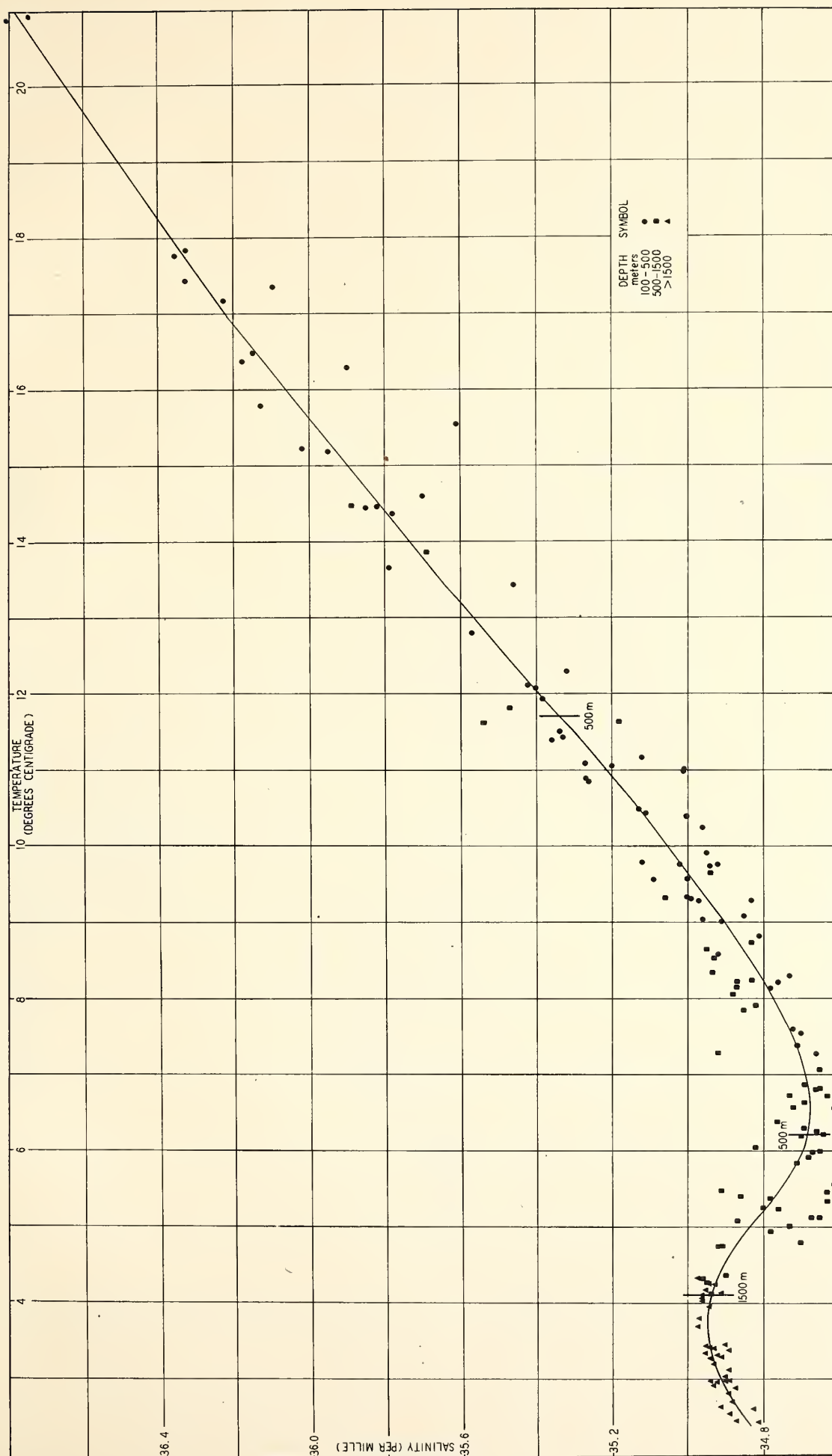
FIG. 3 — COMPOSITE TEMPERATURE-SALINITY RELATION, STATIONS 20–34, ATLANTIC OCEAN AND CARIBBEAN SEA, FROM CARNEGIE RESULTS, 1928
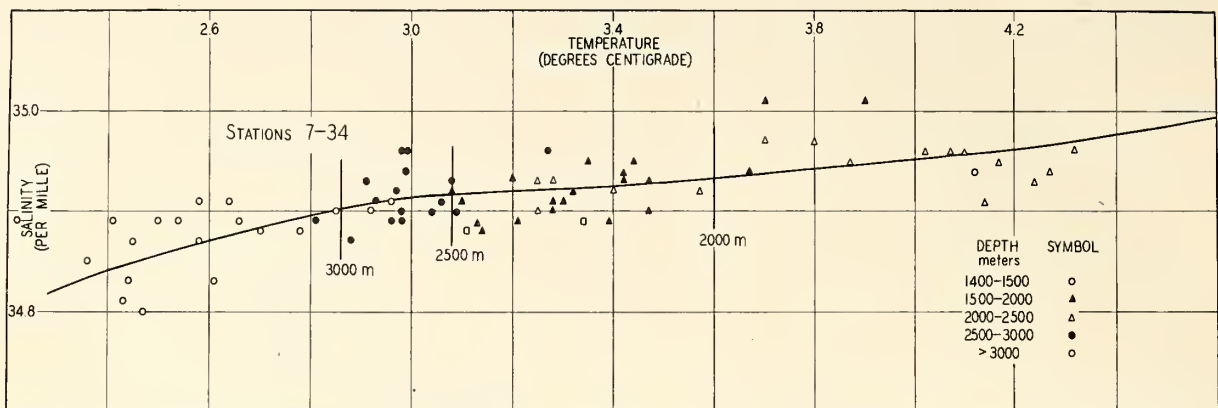
FIG. 4—COMPOSITE TEMPERATURE-SALINITY RELATION, DEEP WATER ATLANTIC OCEAN, FROM CARNEGIE RESULTS, 1928

FIG. 5—DYNAMIC TOPOGRAPHY OF THE 100-DECIBAR SURFACE RELATIVE TO THE 2000-DECIBAR SURFACE, NORTH ATLANTIC OCEAN
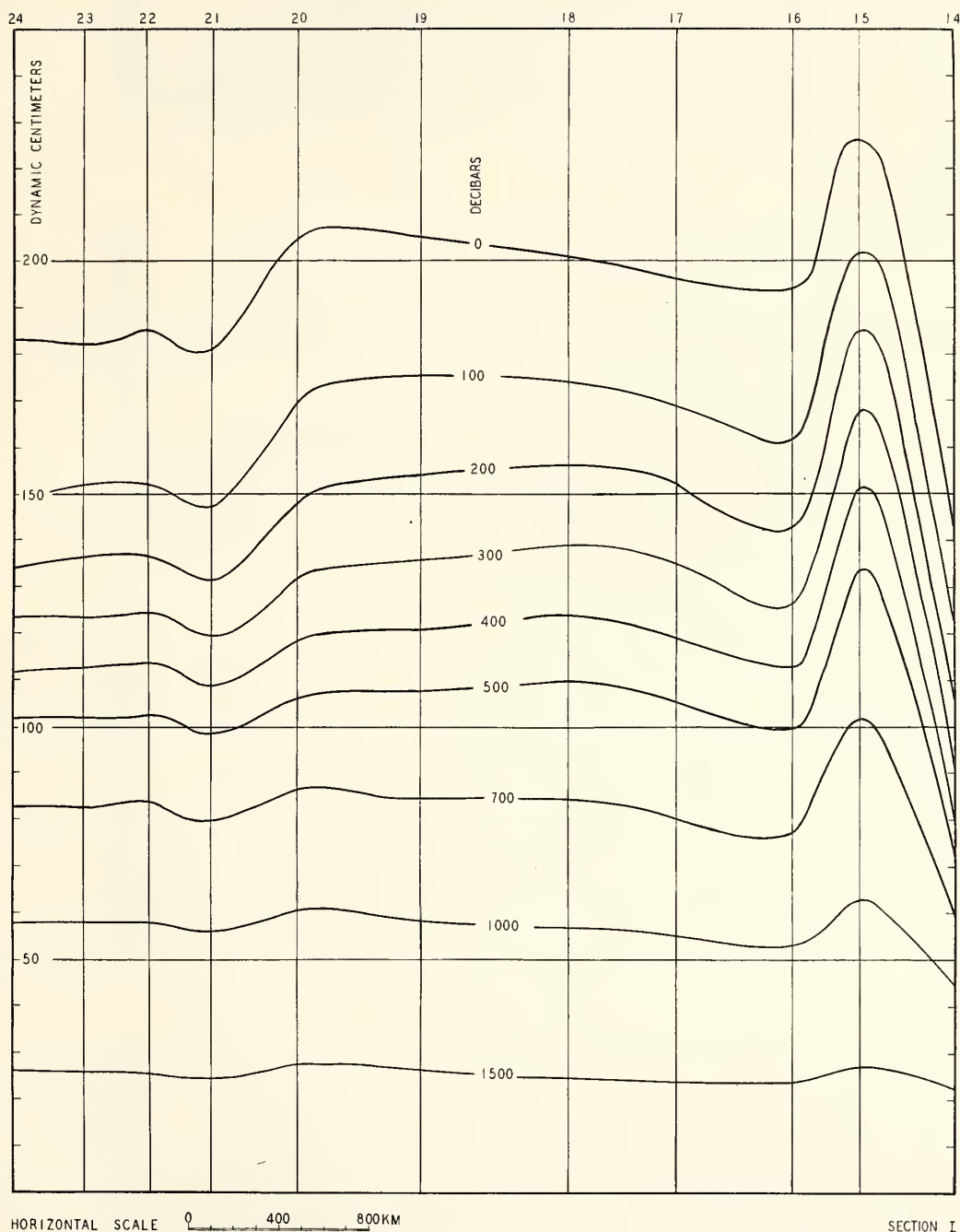
FIG. 6 — PROFILE ISOBARIC SURFACES, ATLANTIC OCEAN, FROM CARNEGIE RESULTS, 1928
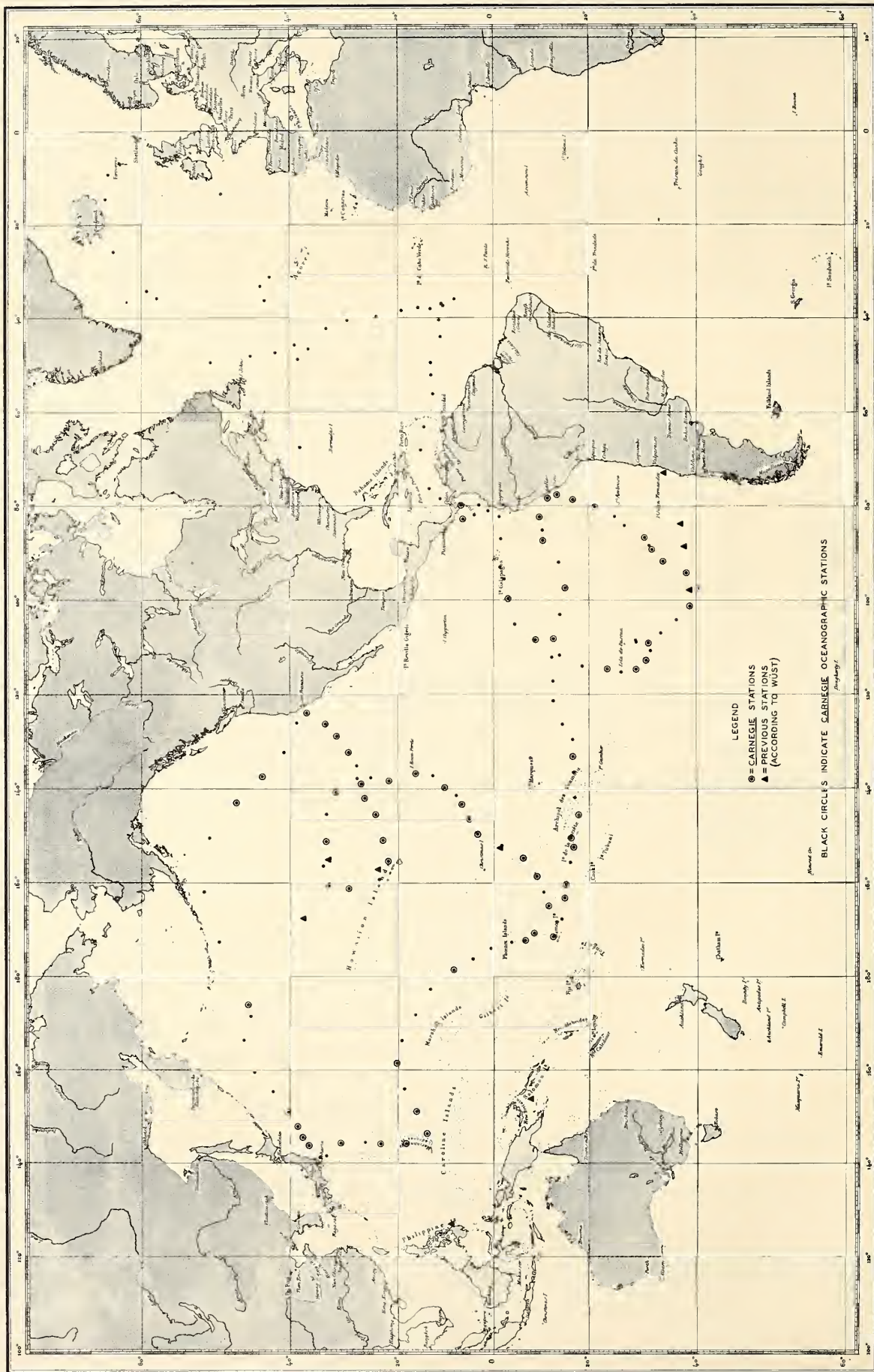
FIG. 7.—STATIONS OF TEMPERATURE AND SALINITY OBSERVATIONS, DEPTHS GREATER THAN 3000 METERS, PACIFIC OCEAN, CARNEGIE AND PREVIOUS VALUES

LEGEND

⊙ = CARNEGIE STATIONS
▲ = PREVIOUS STATIONS
(ACCORDING TO WÜST)

BLACK CIRCLES INDICATE CARNEGIE OCEANOGRAPHIC STATIONS
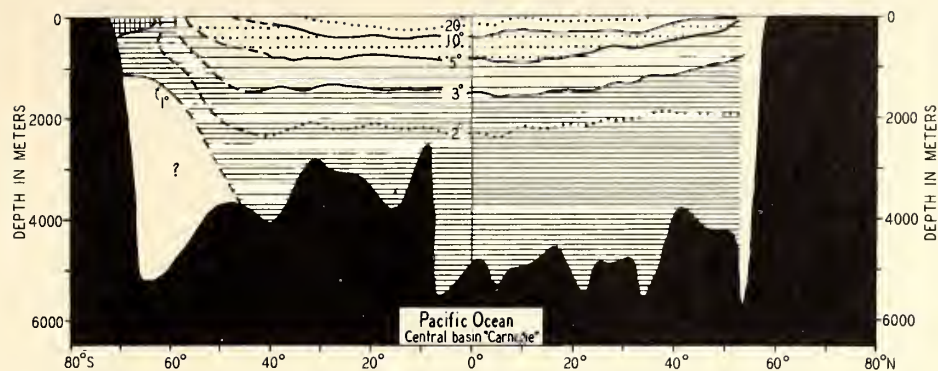
FIG. 8—VERTICAL DISTRIBUTION TEMPERATURE IN CENTRAL PART OF PACIFIC
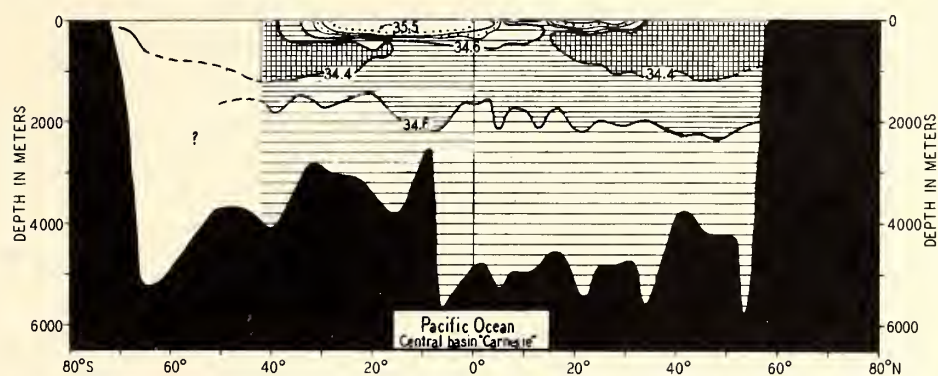
FIG. 9—VERTICAL DISTRIBUTION SALINITY IN CENTRAL PART OF PACIFIC
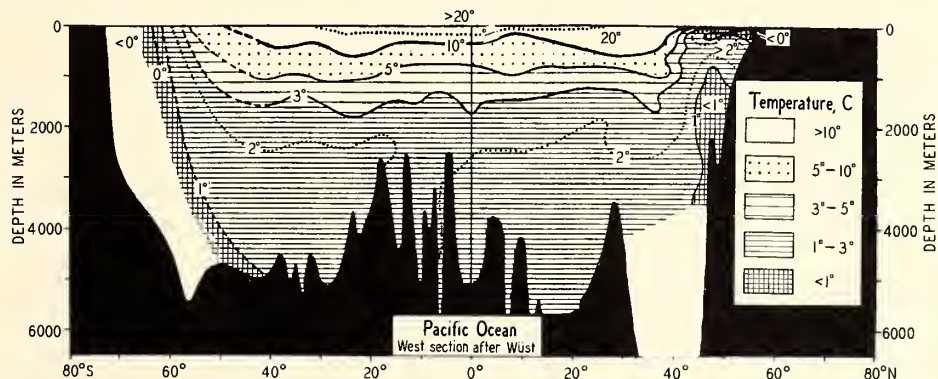
FIG. 10—VERTICAL DISTRIBUTION TEMPERATURE IN WESTERN PART OF PACIFIC
(ACCORDING TO WÜST)
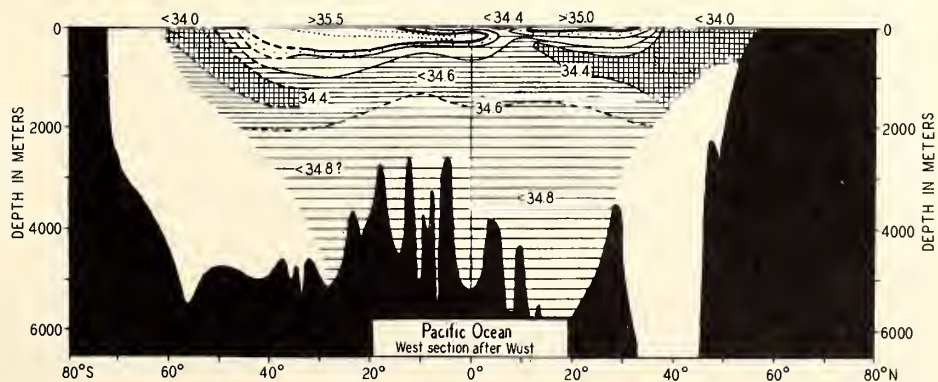
FIG. 11—VERTICAL DISTRIBUTION SALINITY IN WESTERN PART OF PACIFIC
(ACCORDING TO WÜST)
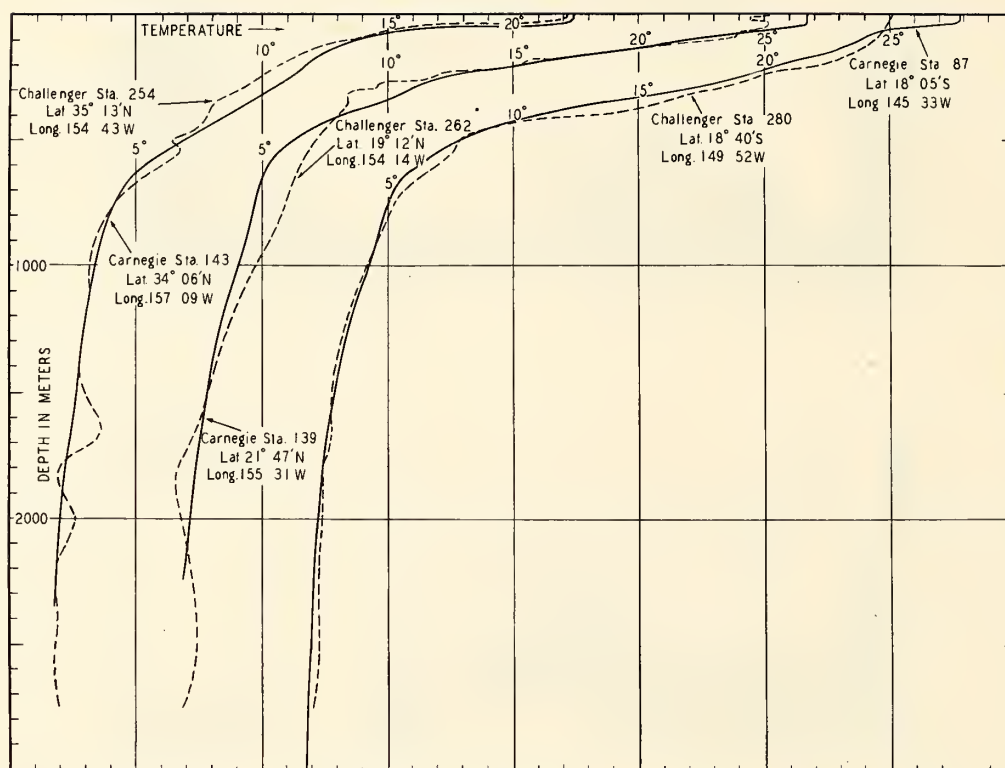
FIG. 12—COMPARISON TEMPERATURE OBSERVATIONS, CHALLENGER, 1875, AND CARNEGIE, 1929
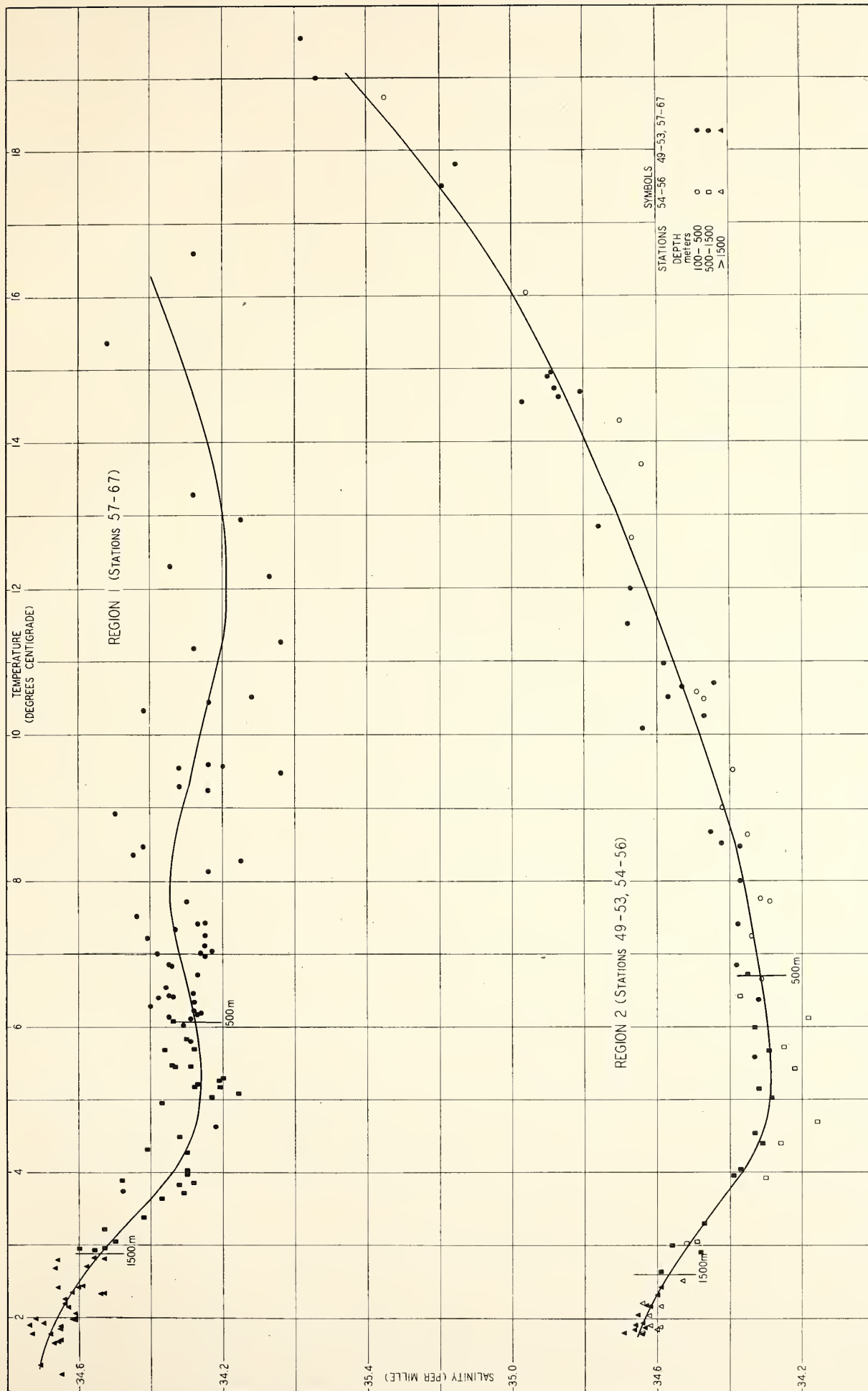
FIG. 13—COMPOSITE TEMPERATURE-SALINITY RELATION, REGIONS 1-2, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1928-1929
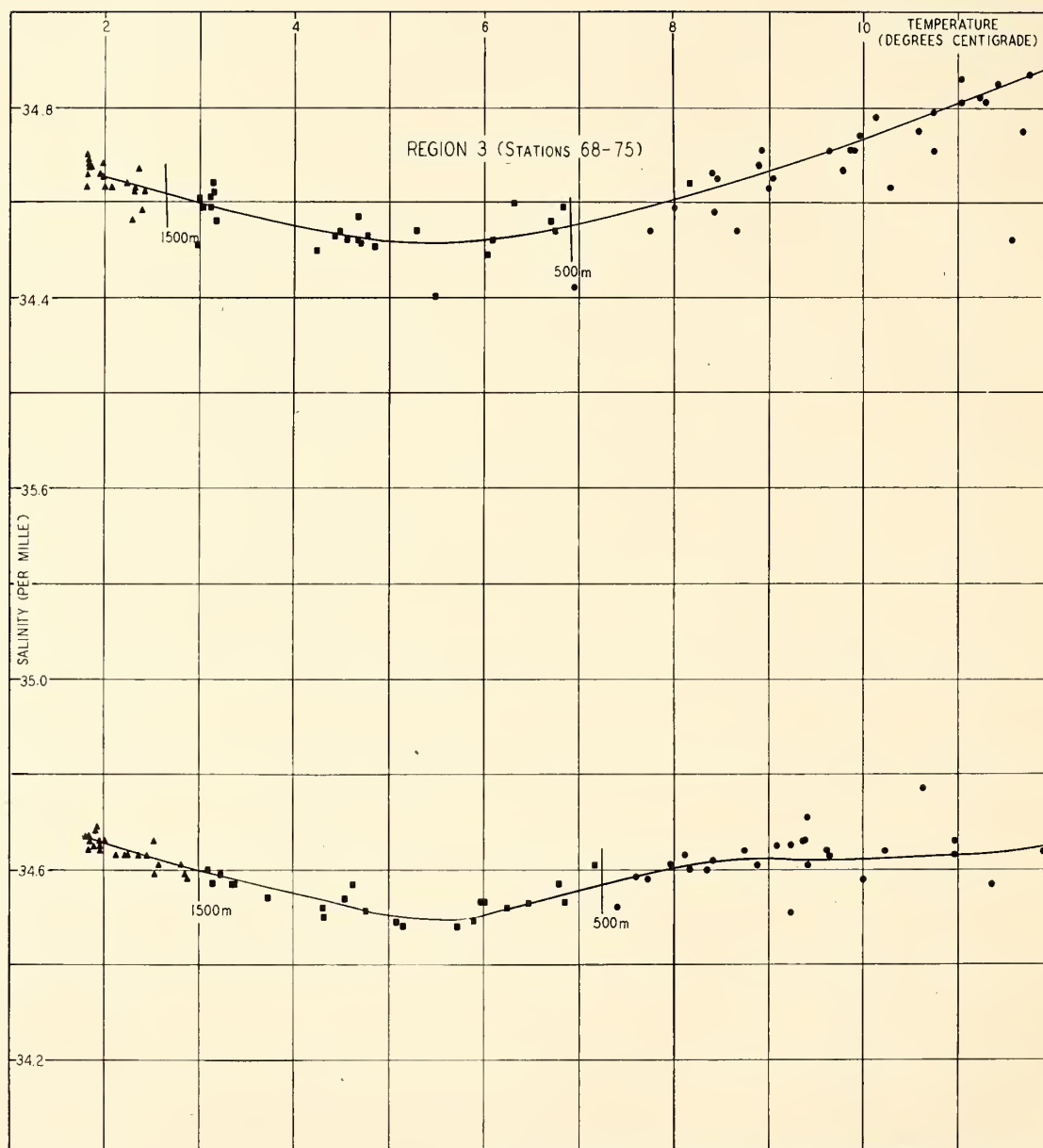
125

FIG. 14 —COMPOSITE TEMPERATURE-SALINITY RELATION, REGIONS
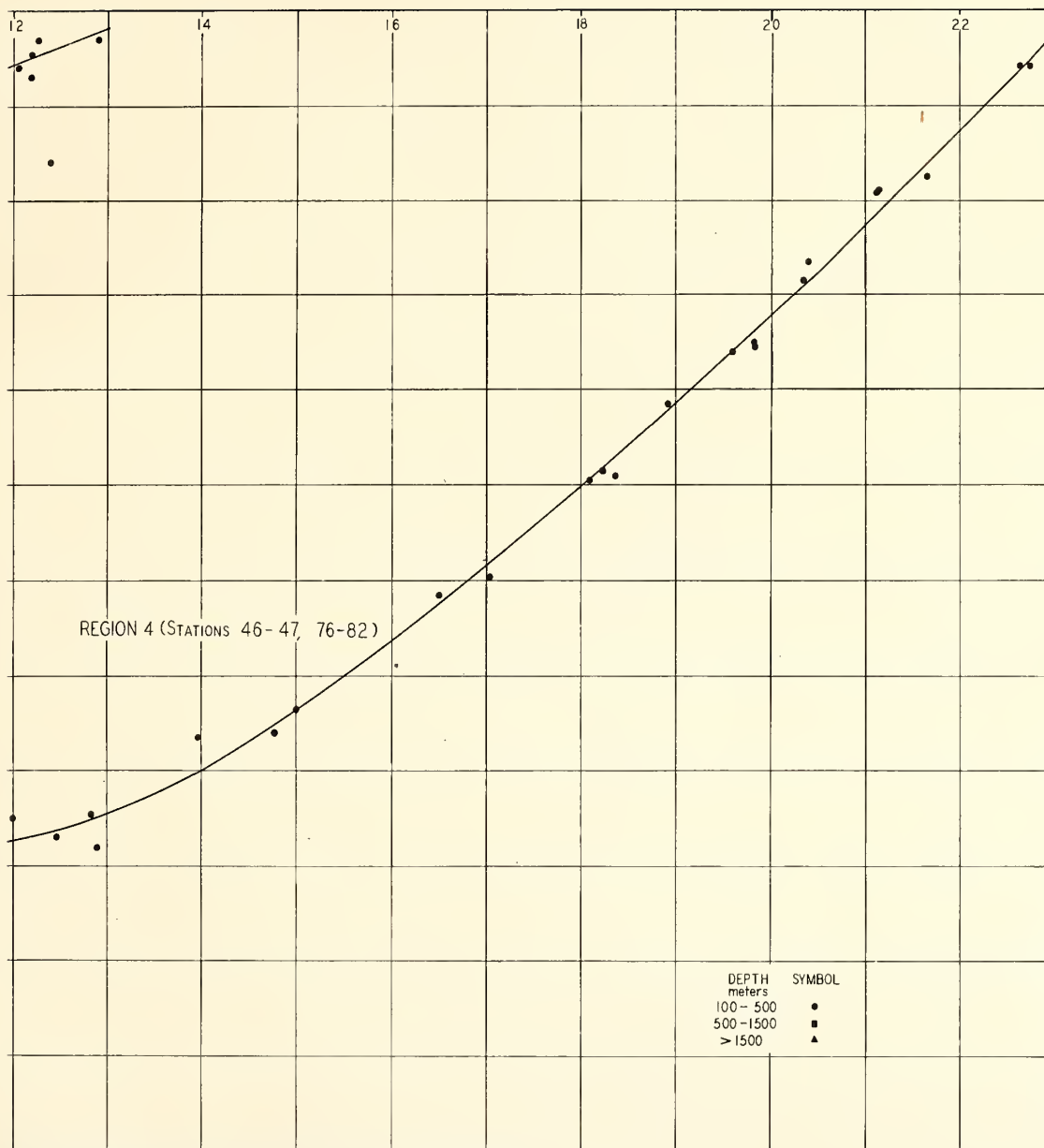
REGION 4 (Stations 46-47, 76-82)

DEPTH   SYMBOL
meters
100 - 500   ●
500 -1500   ■
> 1500   ▲

3-4, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1928–1929

REGION 6 (STATIONS 35-45, 46-48)

FIG. 15—COMPOSITE TEMPERATURE-SALINITY RELATION, REGIONS

REGION 5 (Stations 83-97, 159-162)
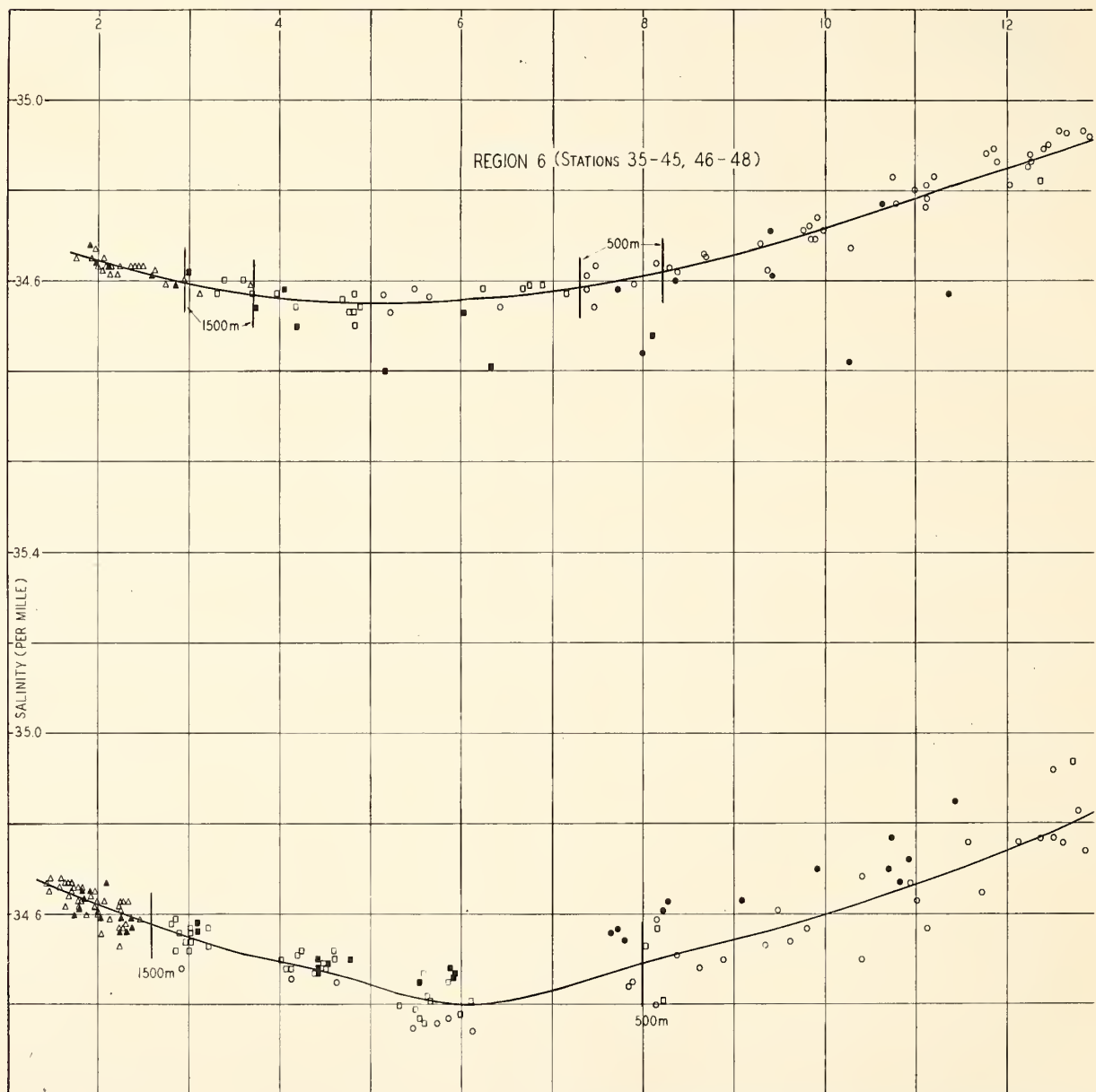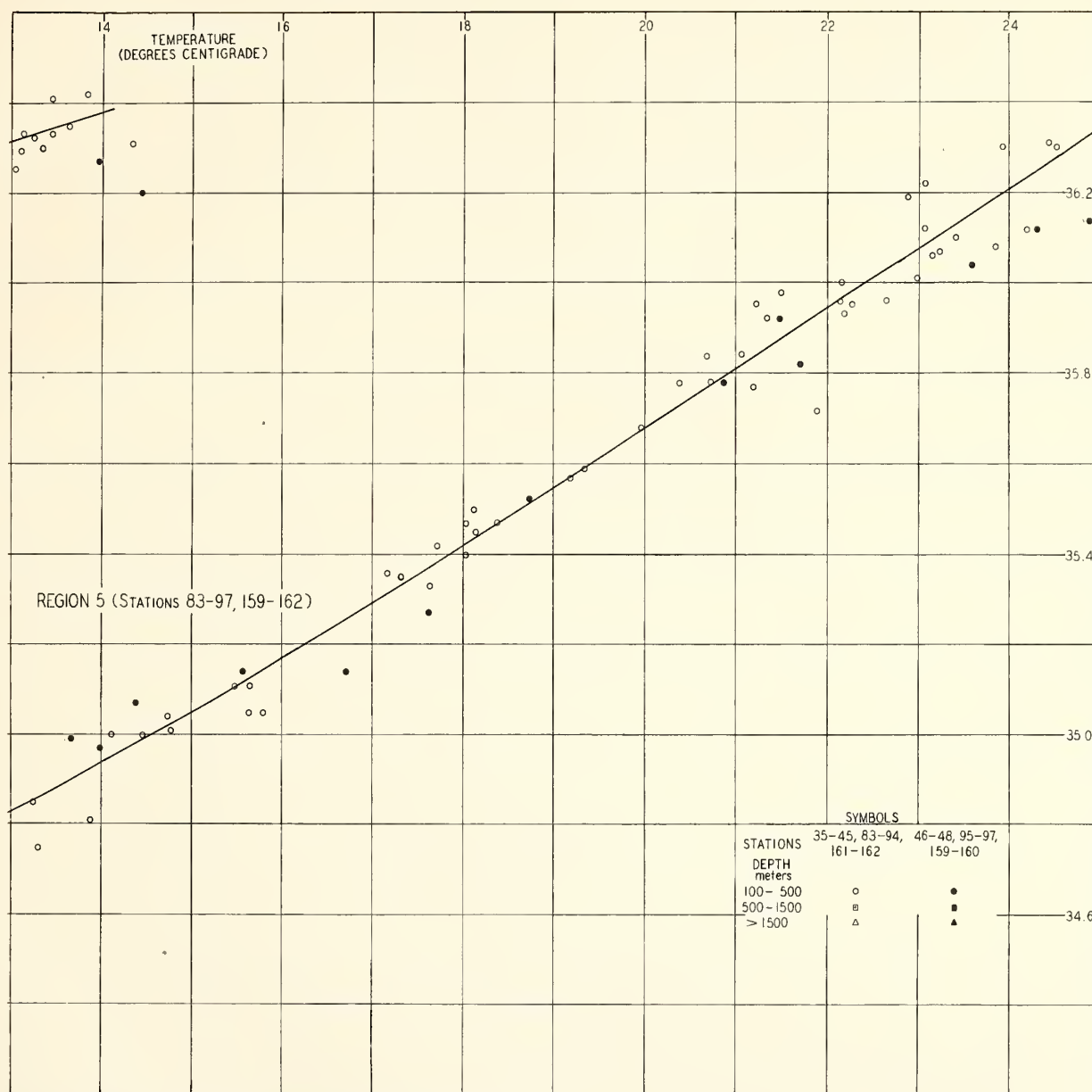
5-6, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1928-1929
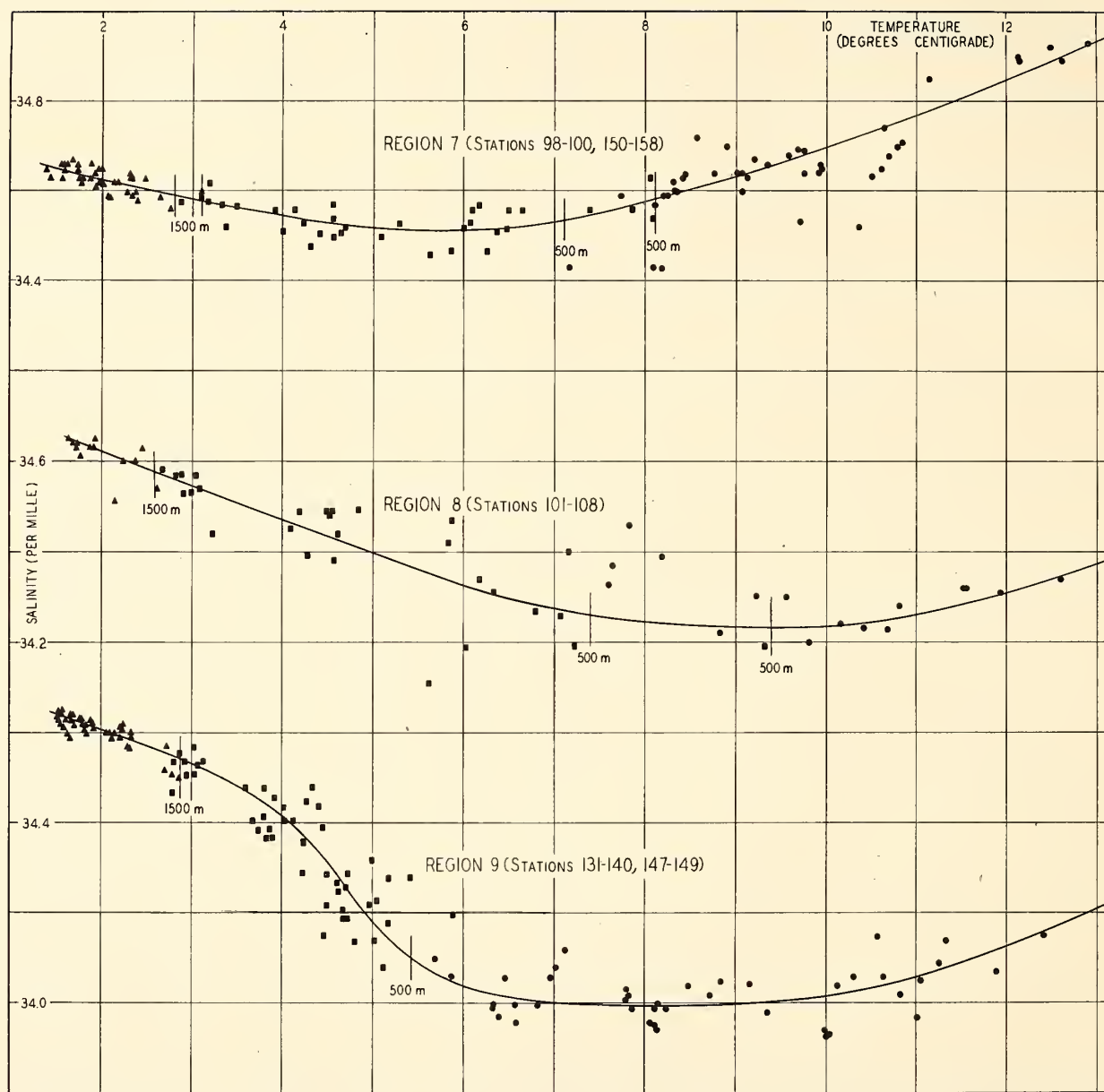
FIG. 16 — COMPOSITE TEMPERATURE-SALINITY RELATION, REGIONS
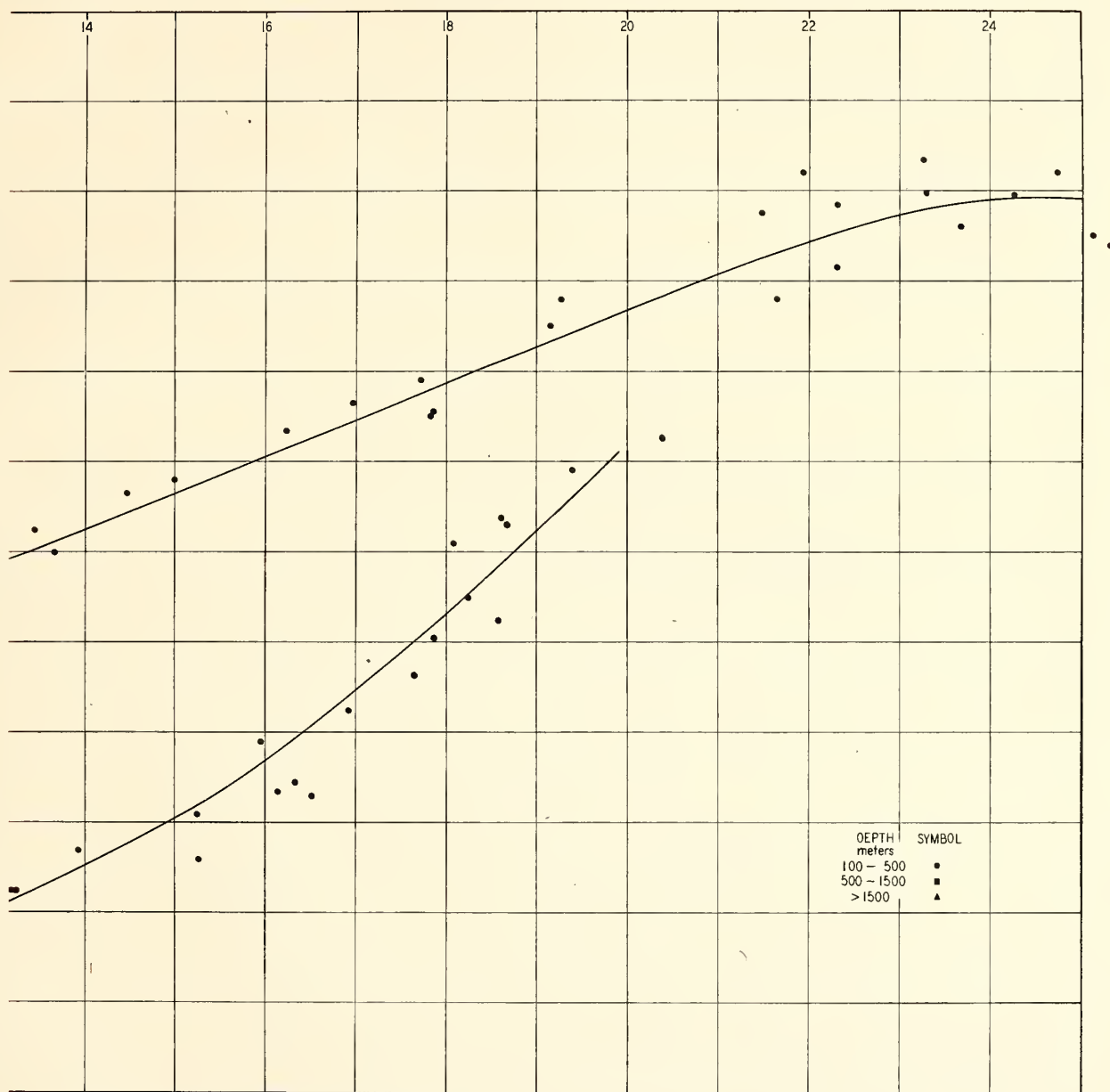
7-9, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1929
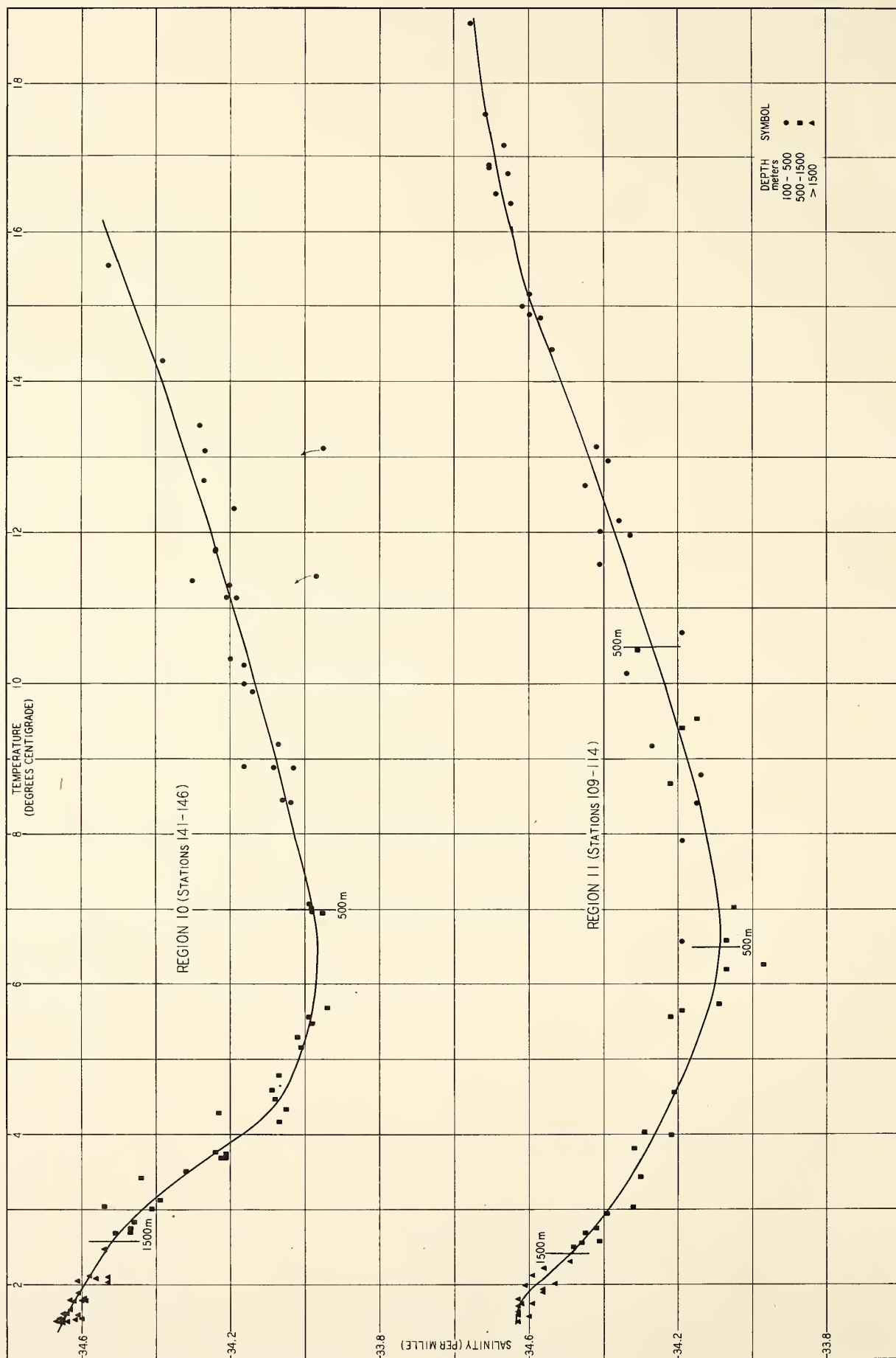
FIG. 17—COMPOSITE TEMPERATURE-SALINITY RELATION, REGIONS 10-11, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1929
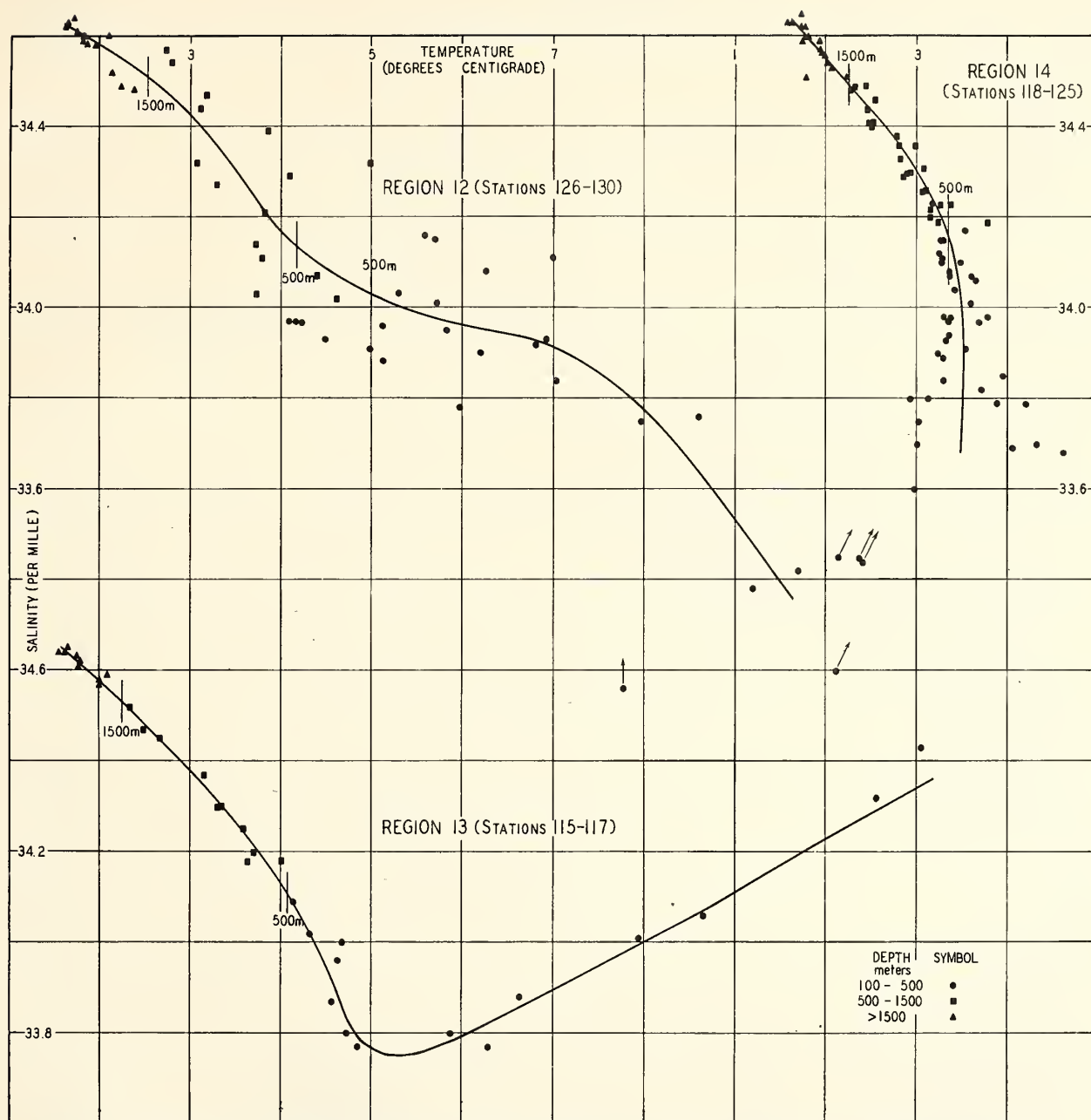
FIG. 18—COMPOSITE TEMPERATURE-SALINITY RELATION, REGIONS 12-14, PACIFIC OCEAN, FROM <u>CARNEGIE</u> RESULTS, 1929
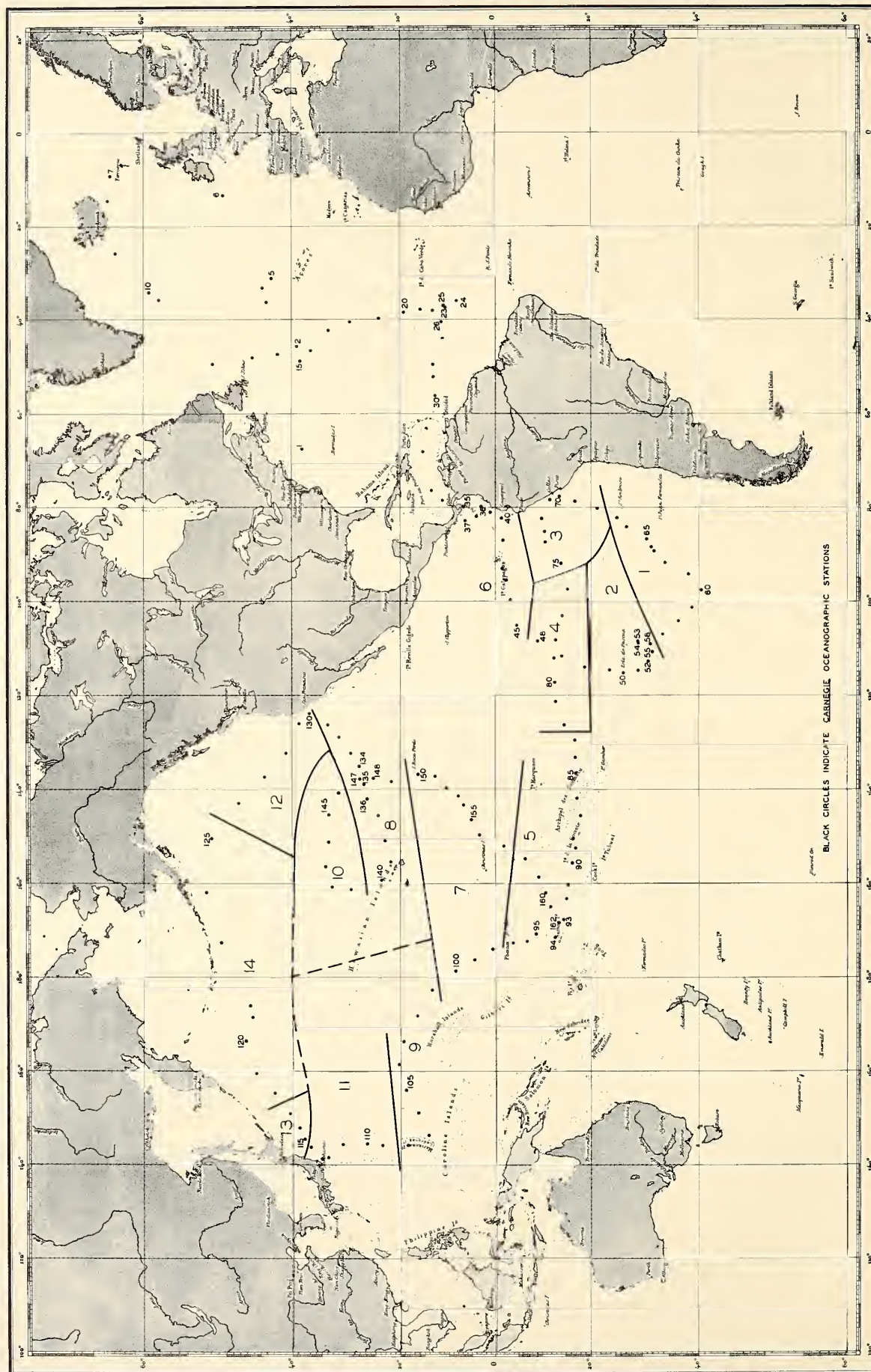
FIG 19—REGIONS WHERE TEMPERATURE-SALINITY RELATION IS NEARLY THE SAME IN EACH REGION, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1928-1929

BLACK CIRCLES INDICATE CARNEGIE OCEANOGRAPHIC STATIONS

134
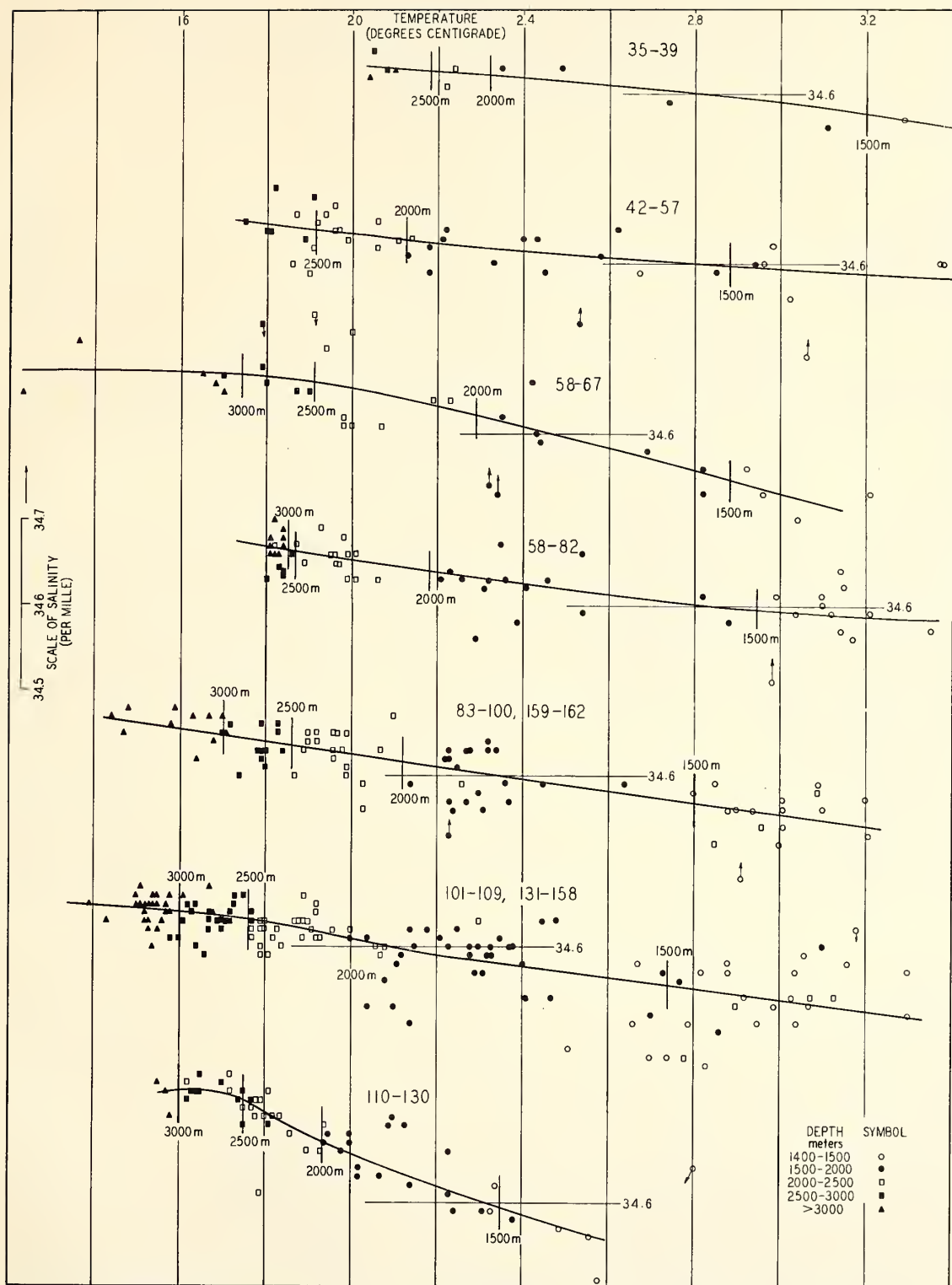
FIG. 20A—COMPOSITE TEMPERATURE-SALINITY RELATION, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1928-1929
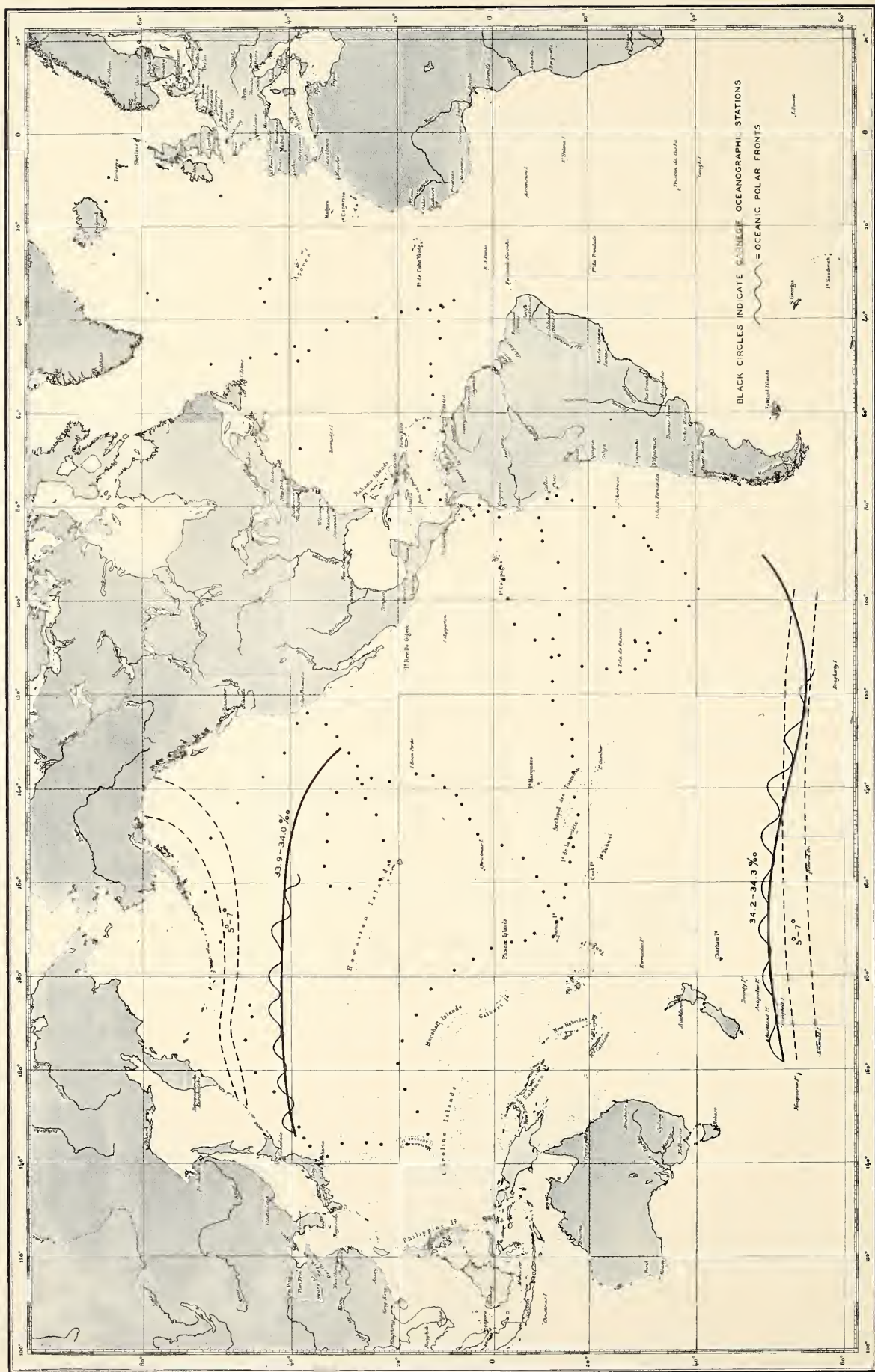
FIG. 20B—SURFACE TEMPERATURES AND SALINITIES CORRESPONDING TO CHARACTERISTIC VALUES OF INTERMEDIATE WATER IN BOTH HEMISPHERES
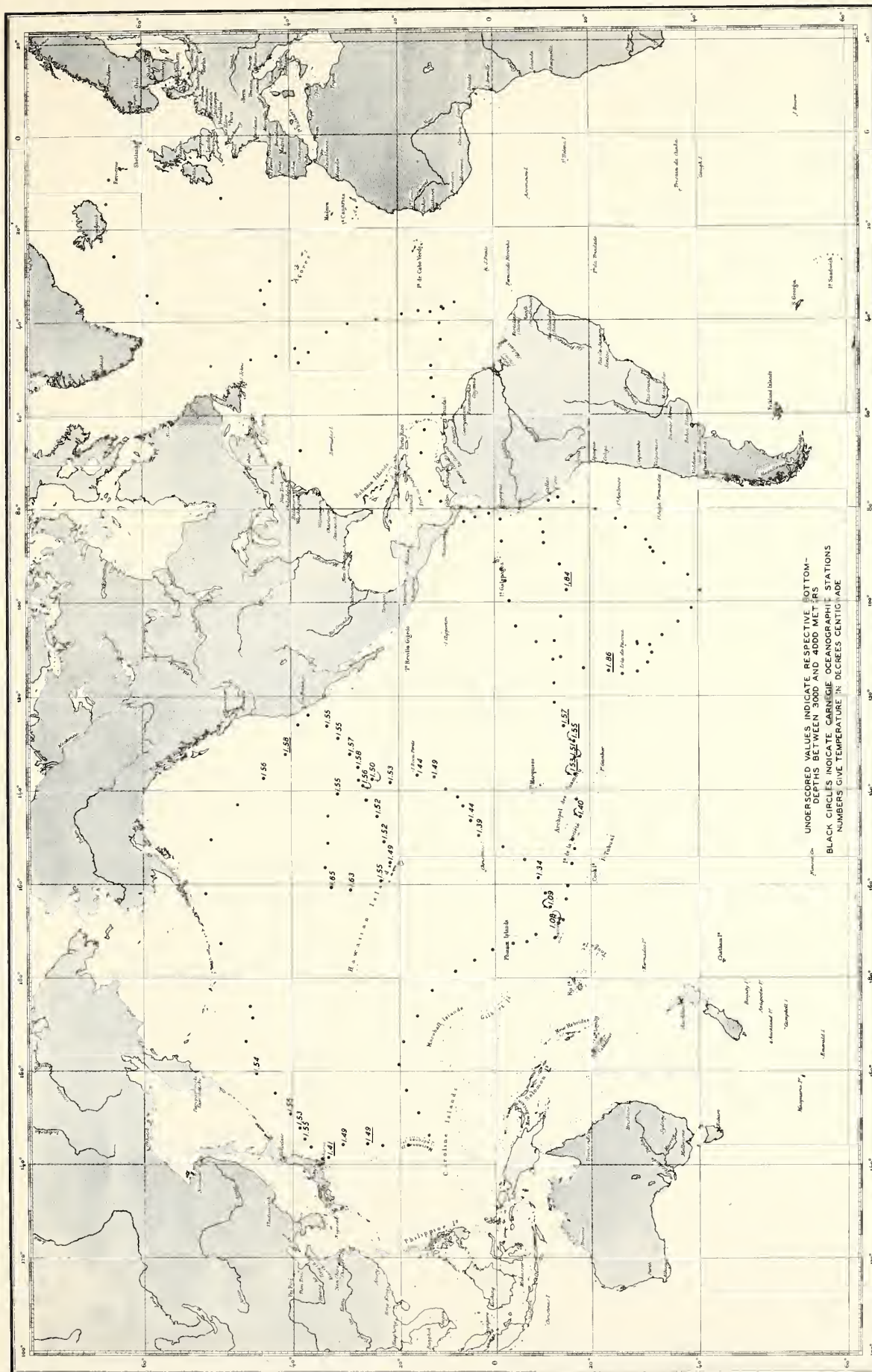
FIG. 21—BOTTOM TEMPERATURES OF WATER FOR BOTTOM DEPTHS GREATER THAN 3000 METERS, PACIFIC OCEAN, FROM CARNEGIE RESULTS, 1929

UNDERSCORED VALUES INDICATE RESPECTIVE BOTTOM—
DEPTHS BETWEEN 3000 AND 4000 METERS
BLACK CIRCLES INDICATE CARNEGIE OCEANOGRAPHIC STATIONS
NUMBERS GIVE TEMPERATURE IN DEGREES CENTIGRADE
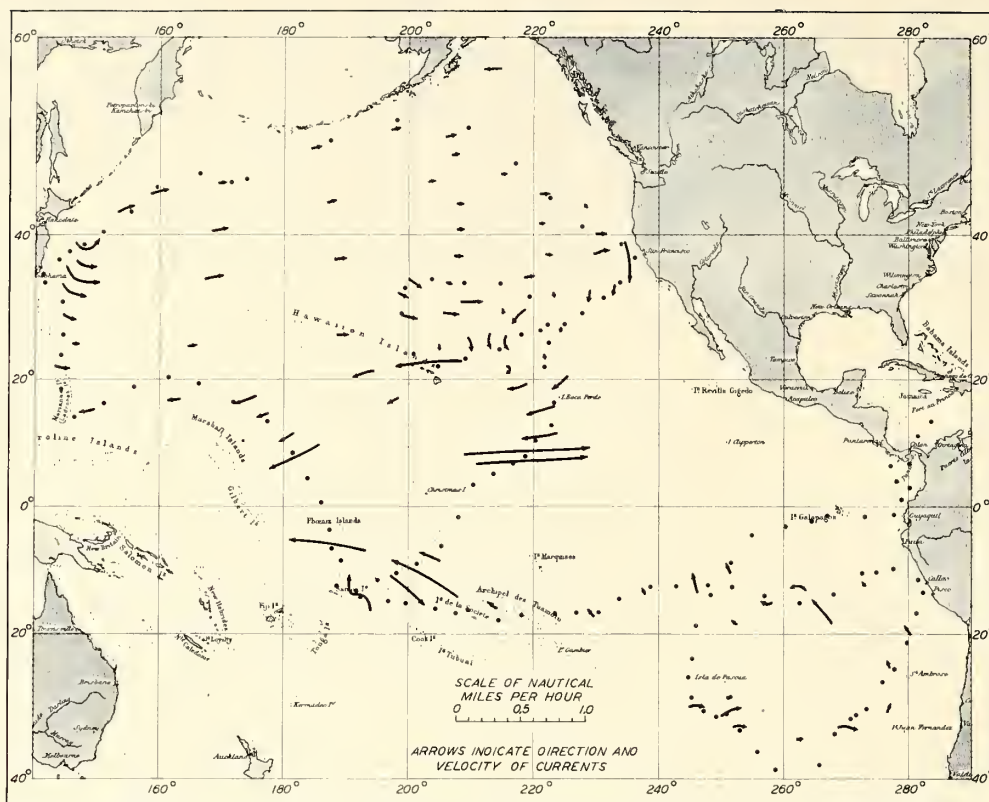
FIG. 22—CURRENT-CHART, PACIFIC OCEAN, FROM OBSERVATIONS OF SALINITY AND TEMPERATURE OF SEA WATER BY THE CARNEGIE, 1928—1929
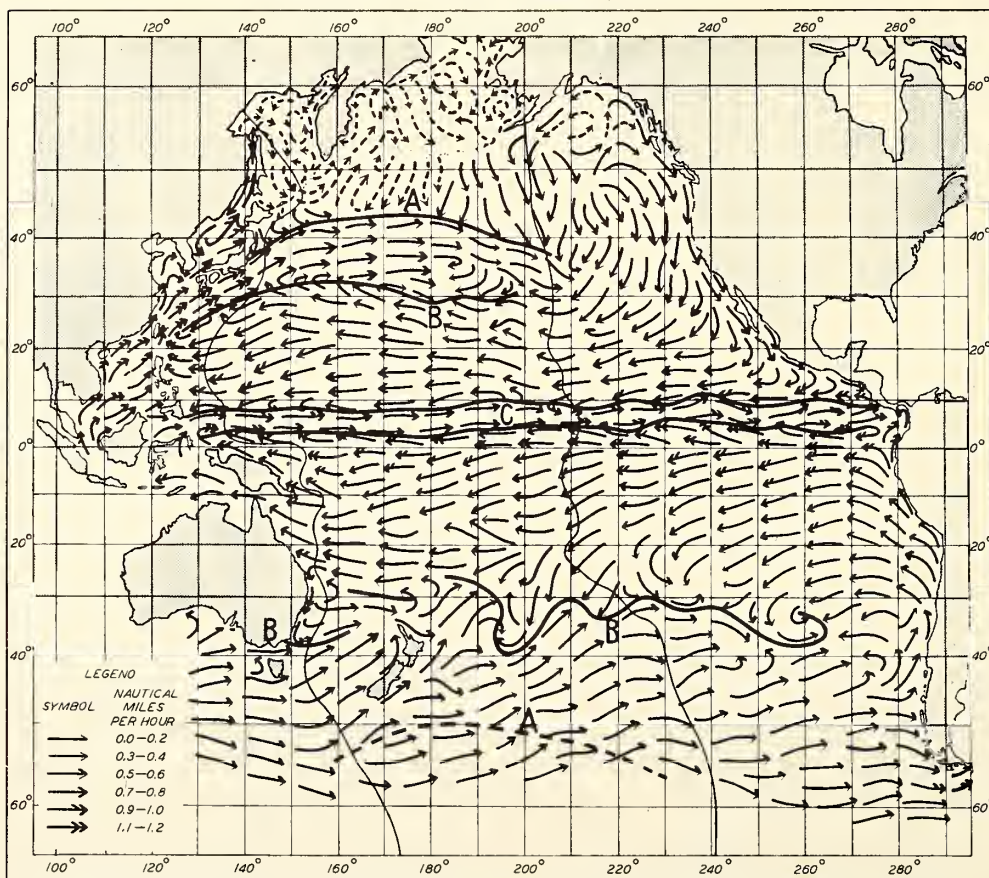
FIG. 23—PACIFIC CURRENTS IN NORTHERN SUMMER FROM PRELIMINARY SKETCH BY A. MERTZ

——— LONGITUDINAL CROSS-SECTION; ——A—— NORTHERLY POLAR FRONT; — —A— — SOUTHERNLY POLAR FRONT; ——B—— SUBTROPICAL CONVERGENCE; ——C—— LIMITS OF EQUATORIAL COUNTER-CURRENT

SOUTH EQUATOR NORTH a

WEST
WEST WEST

SOUTH EQUATOR NORTH b

LEGEND

HATCHED AREA——HEAVY WATER
LIGHT CURVED LINES——PROFILES ISOBARIC SURFACES
WEST, EAST——DIRECTION TOWARD WHICH CURRENT RUNS

SOUTH EQUATOR NORTH c

EAST
WEST WEST
WEST

SOUTH EQUATOR NORTH d

EAST
WEST WEST
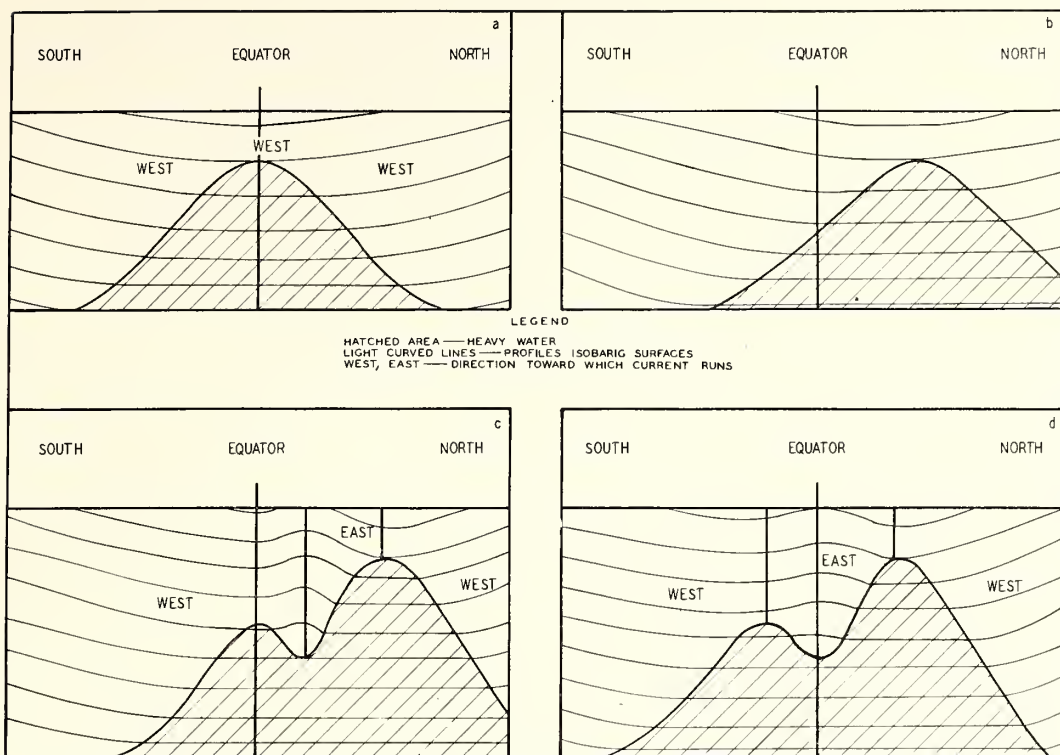
FIG. 24—SCHEMATIC REPRESENTATION POSSIBLE FIELDS DENSITY AND PRESSURE, VINCINITY OF EQUATOR,
FROM CARNEGIE RESULTS, 1928–1929

159   158   157   156 155 154 153 152   151   150   149
SOUTH   EQUATOR   NORTH

DEPTH IN METERS

DECIBARS

0

100

50

100

150

200

250

300

HORIZONTAL SCALE   0   400   800KM
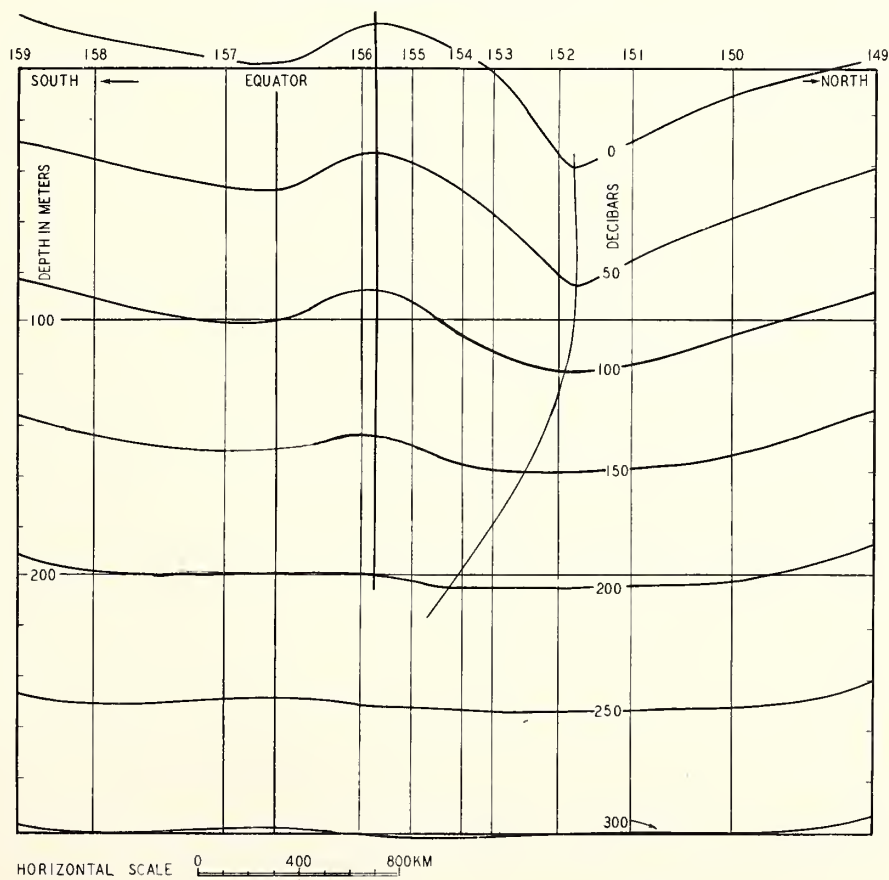
FIG. 25—PROFILE ISOBARIC SURFACES, FROM CARNEGIE RESULTS, 1929

139
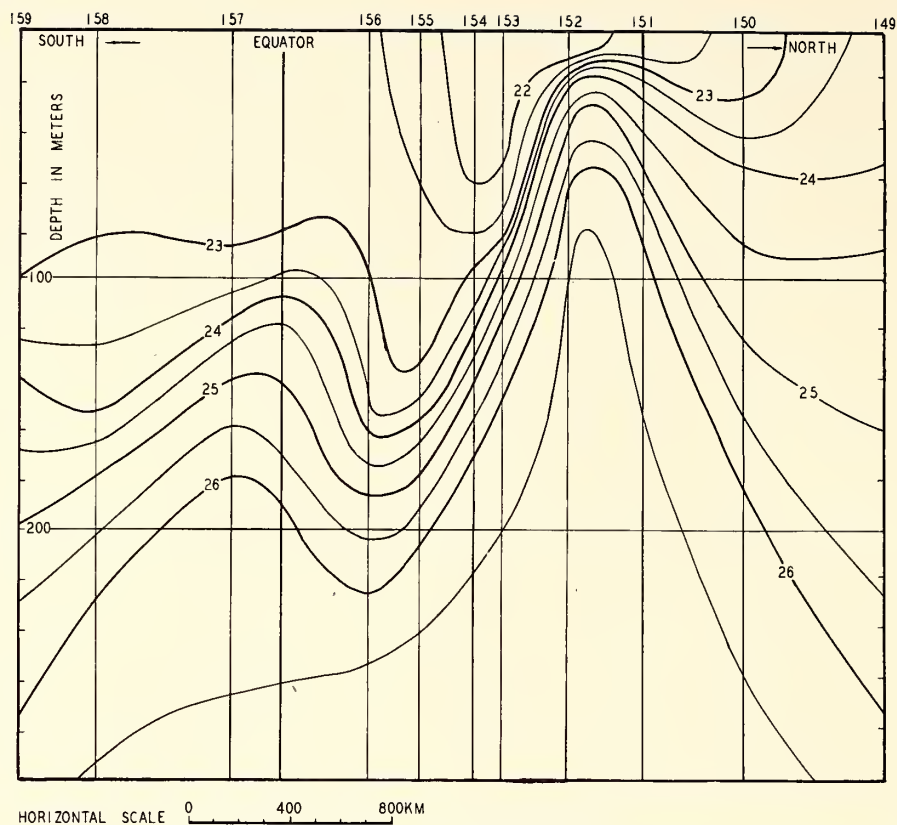
FIG. 26—VERTICAL DISTRIBUTION DENSITY, NORTH-SOUTH SECTION CROSSING EQUATOR, FROM CARNEGIE RESULTS, 1929
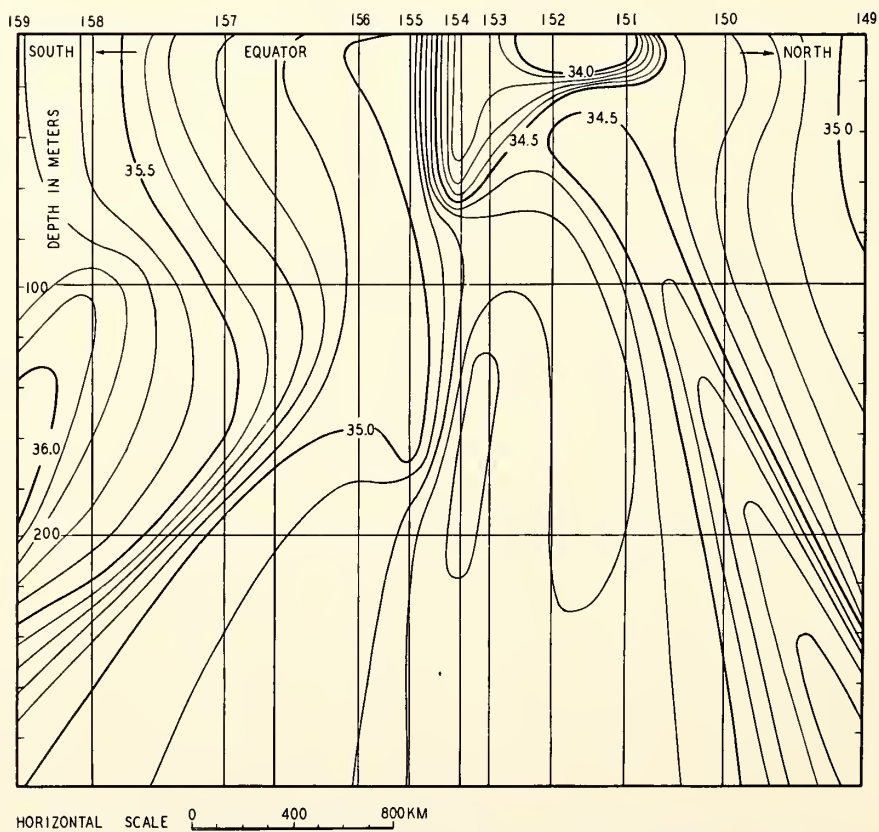
FIG. 27—VERTICAL DISTRIBUTION SALINITY, NORTH-SOUTH SECTION CROSSING EQUATOR, FROM CARNEGIE RESULTS 1929
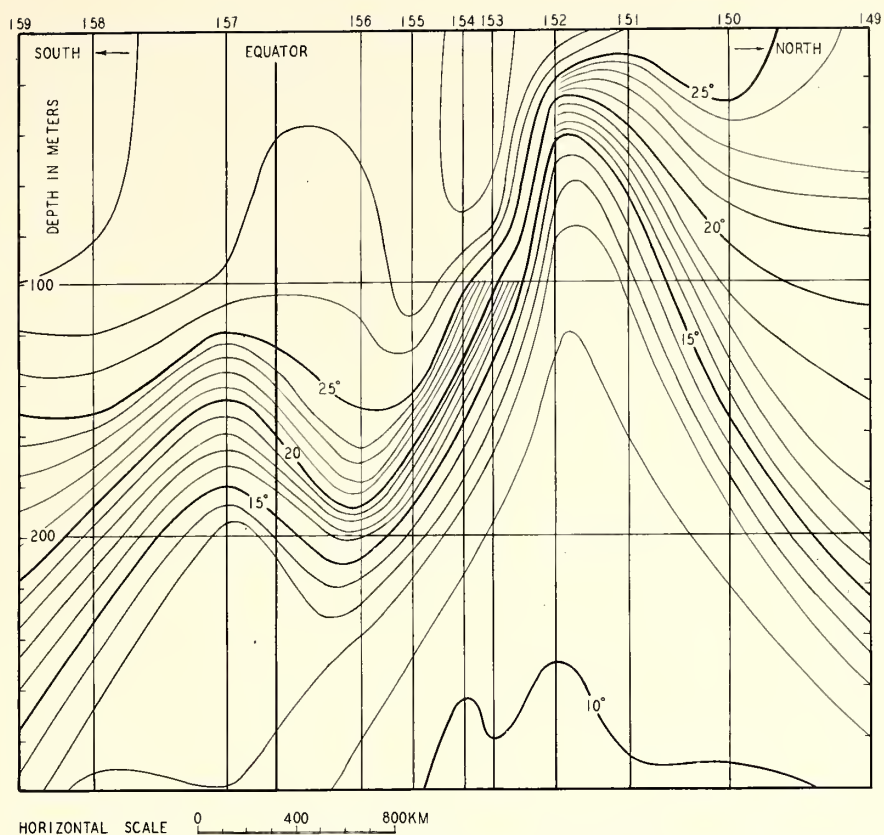
FIG. 28—VERTICAL DISTRIBUTION TEMPERATURE, NORTH-SOUTH SECTION CROSSING EQUATOR, FROM CARNEGIE RESULTS, 1929
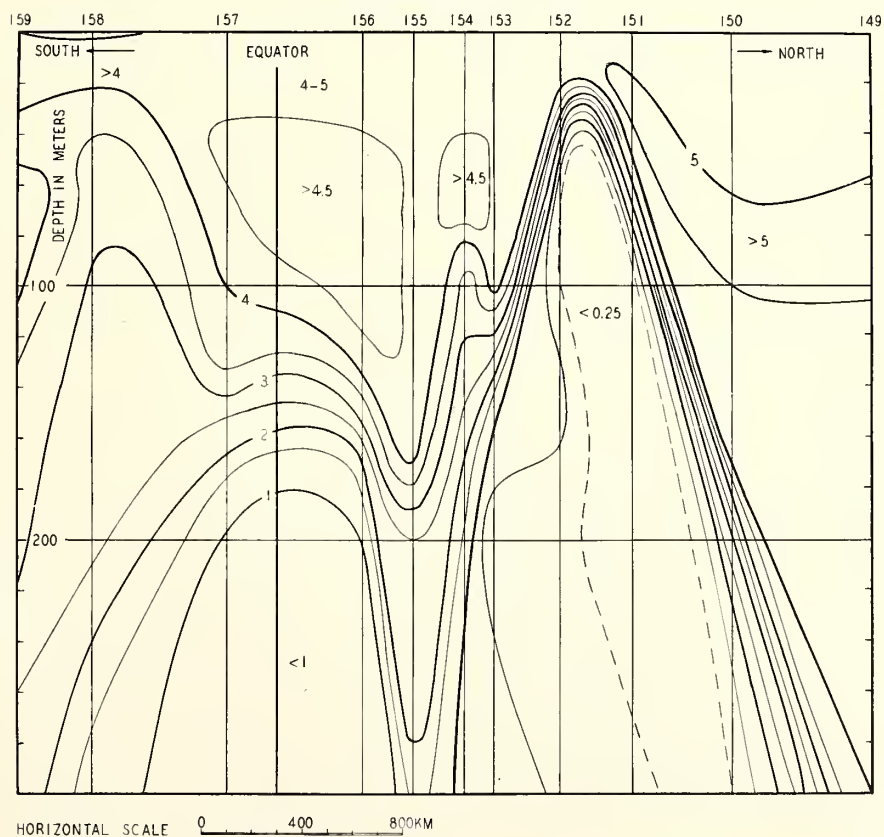
FIG. 29—VERTICAL DISTRIBUTION OXYGEN, NORTH-SOUTH SECTION CROSSING EQUATOR, FROM CARNEGIE RESULTS, 1929
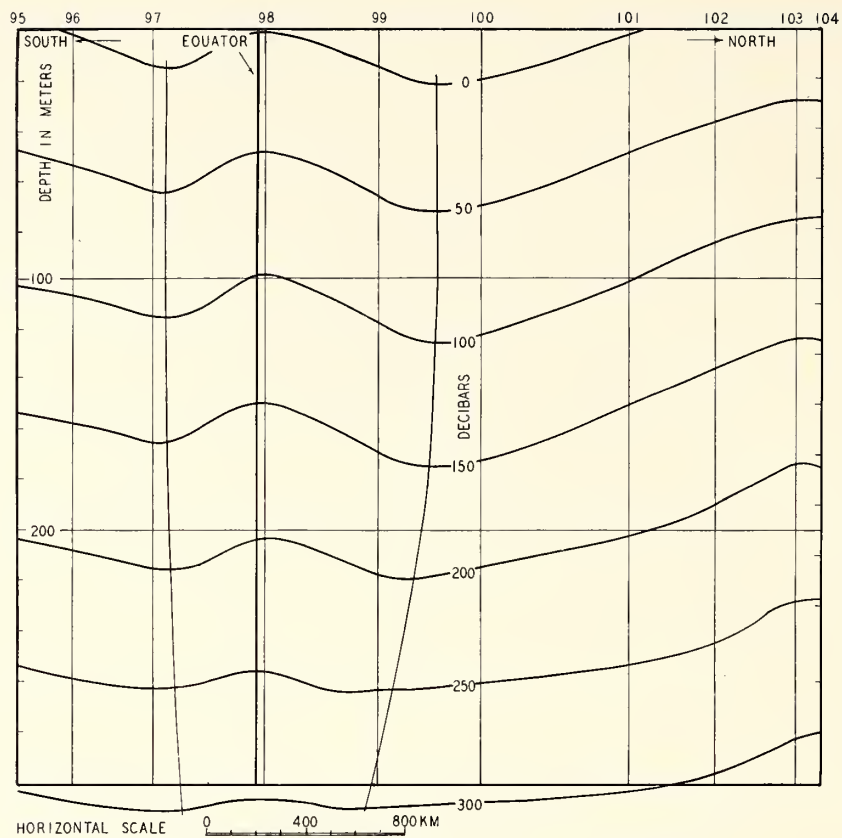
FIG. 30—PROFILE ISOBARIC SURFACES, FROM CARNEGIE RESULTS, 1929
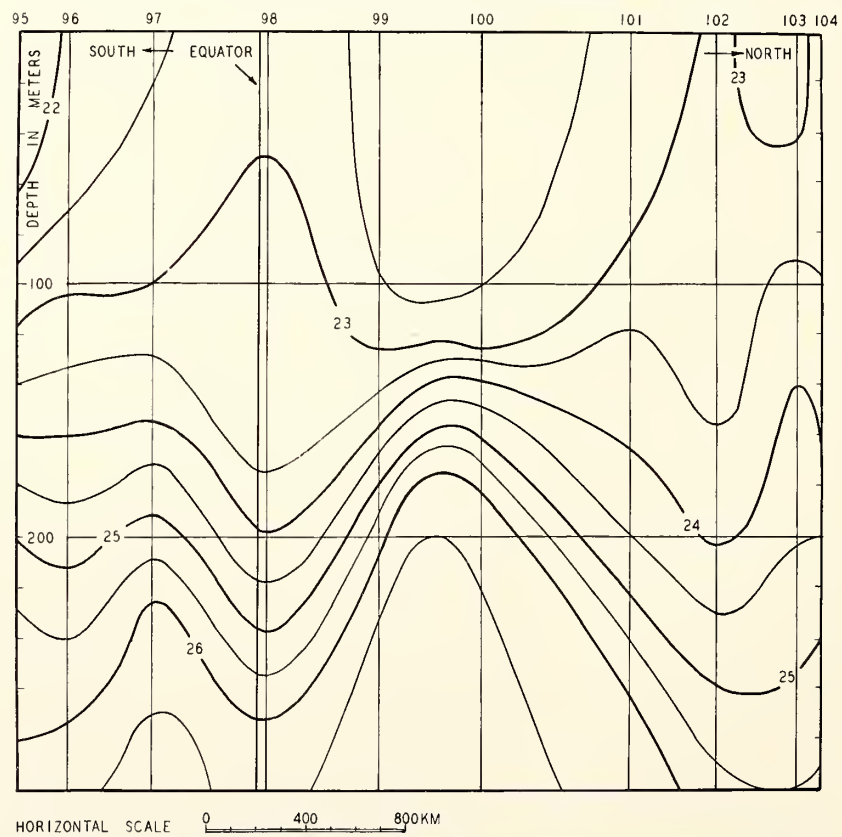
FIG. 31—VERTICAL DISTRIBUTION DENSITY, NORTH-SOUTH SECTION CROSSING EQUATOR,
FROM CARNEGIE RESULTS, 1929

142
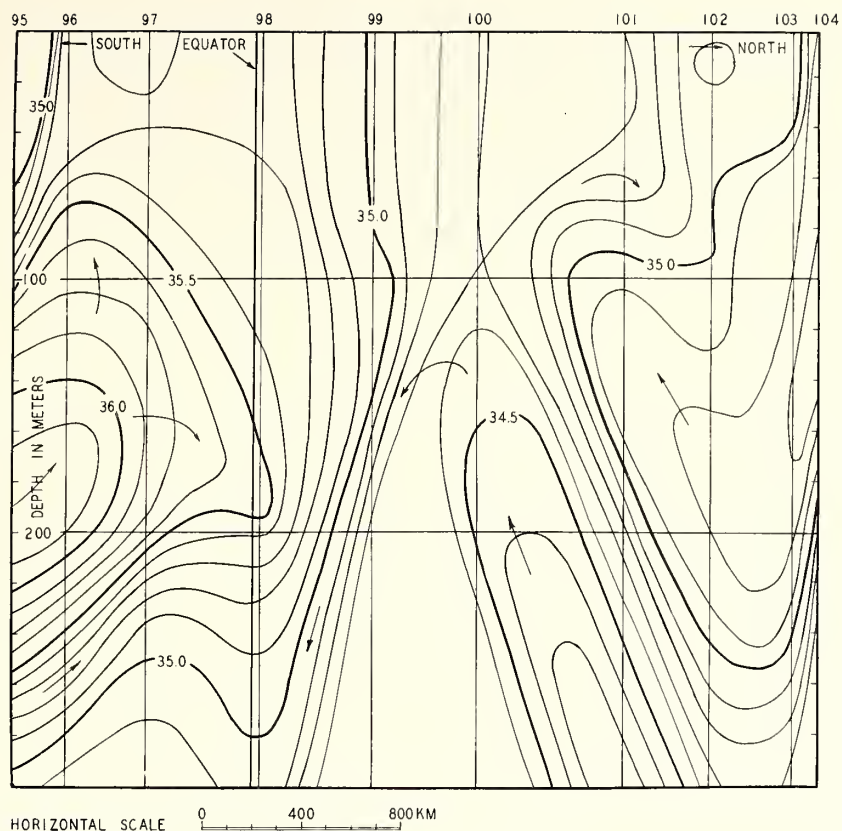
FIG. 32–VERTICAL DISTRIBUTION SALINITY, NORTH-SOUTH SECTION CROSSING EQUATOR, FROM CARNEGIE RESULTS, 1929
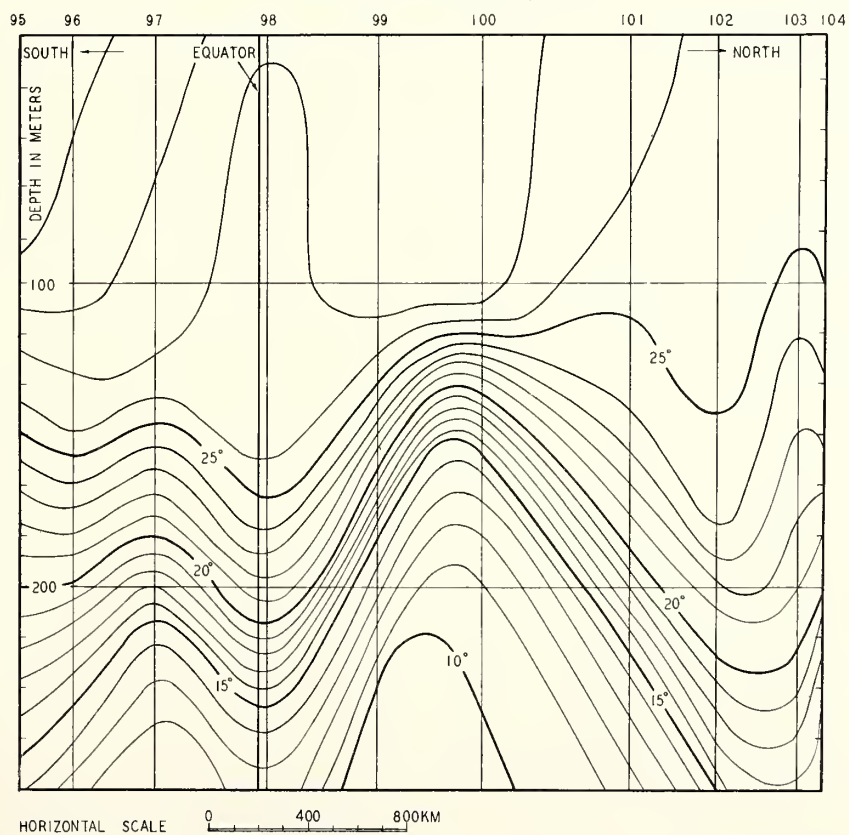
FIG. 33—VERTICAL DISTRIBUTION TEMPERATURE, NORTH-SOUTH SECTION CROSSING EQUATOR, FROM CARNEGIE RESULTS, 1929
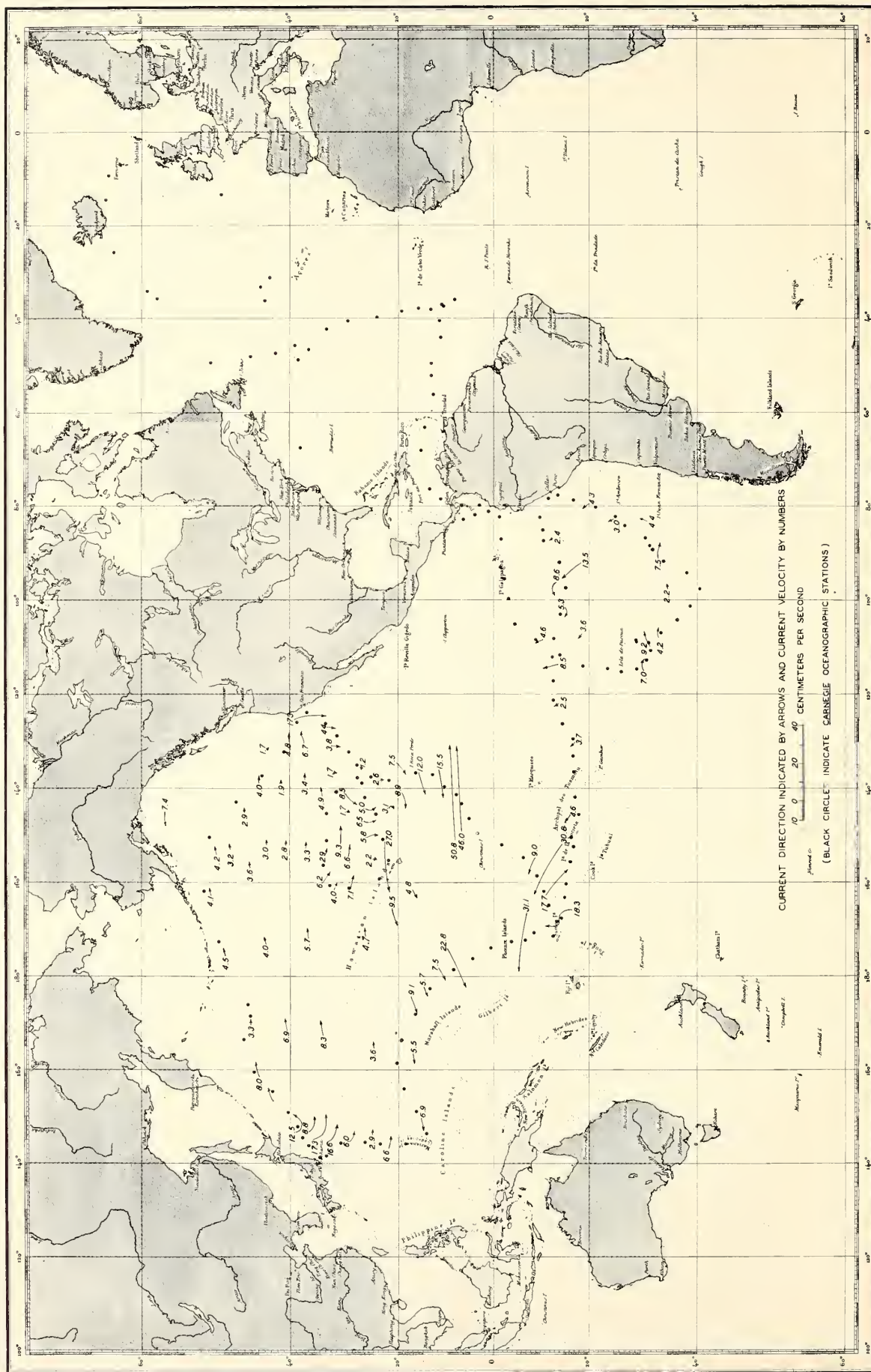
FIG.34—CURRENT-CHART, PACIFIC OCEAN, AT SURFACE RELATIVE TO ASSUMED ZERO CURRENT AT 2000 METERS, FROM CARNEGIE RESULTS, 1928—1929

CURRENT DIRECTION INDICATED BY ARROWS AND CURRENT VELOCITY BY NUMBERS

10 0 20 40
CENTIMETERS PER SECOND

(BLACK CIRCLE INDICATE CARNEGIE OCEANOGRAPHIC STATIONS)

144

FIG. 35.—CURRENT-CHART, PACIFIC OCEAN, AT 100 METERS RELATIVE TO ASSUMED ZERO CURRENT AT 2000 METERS, FROM CARNEGIE RESULTS, 1928-1929

145
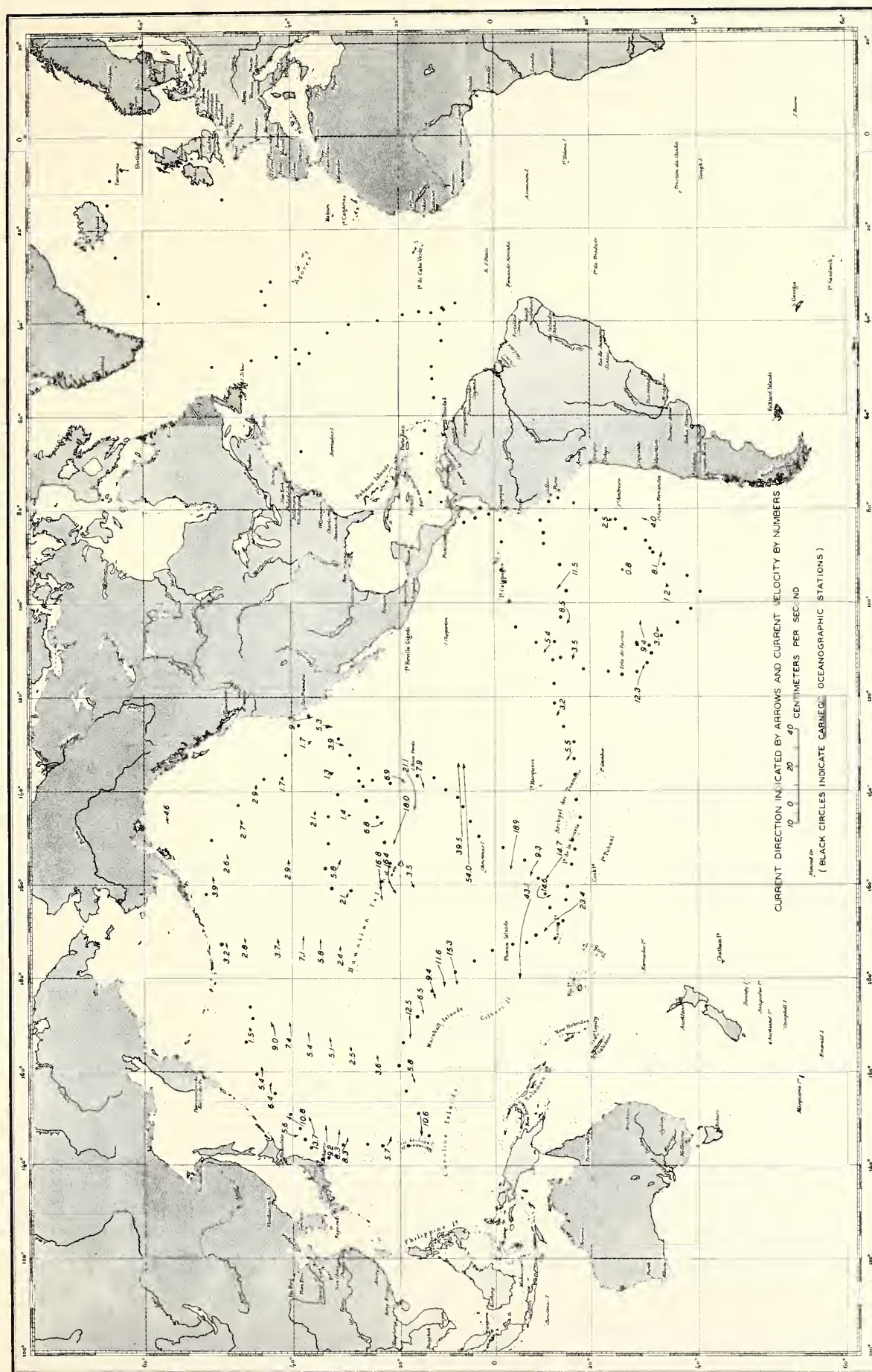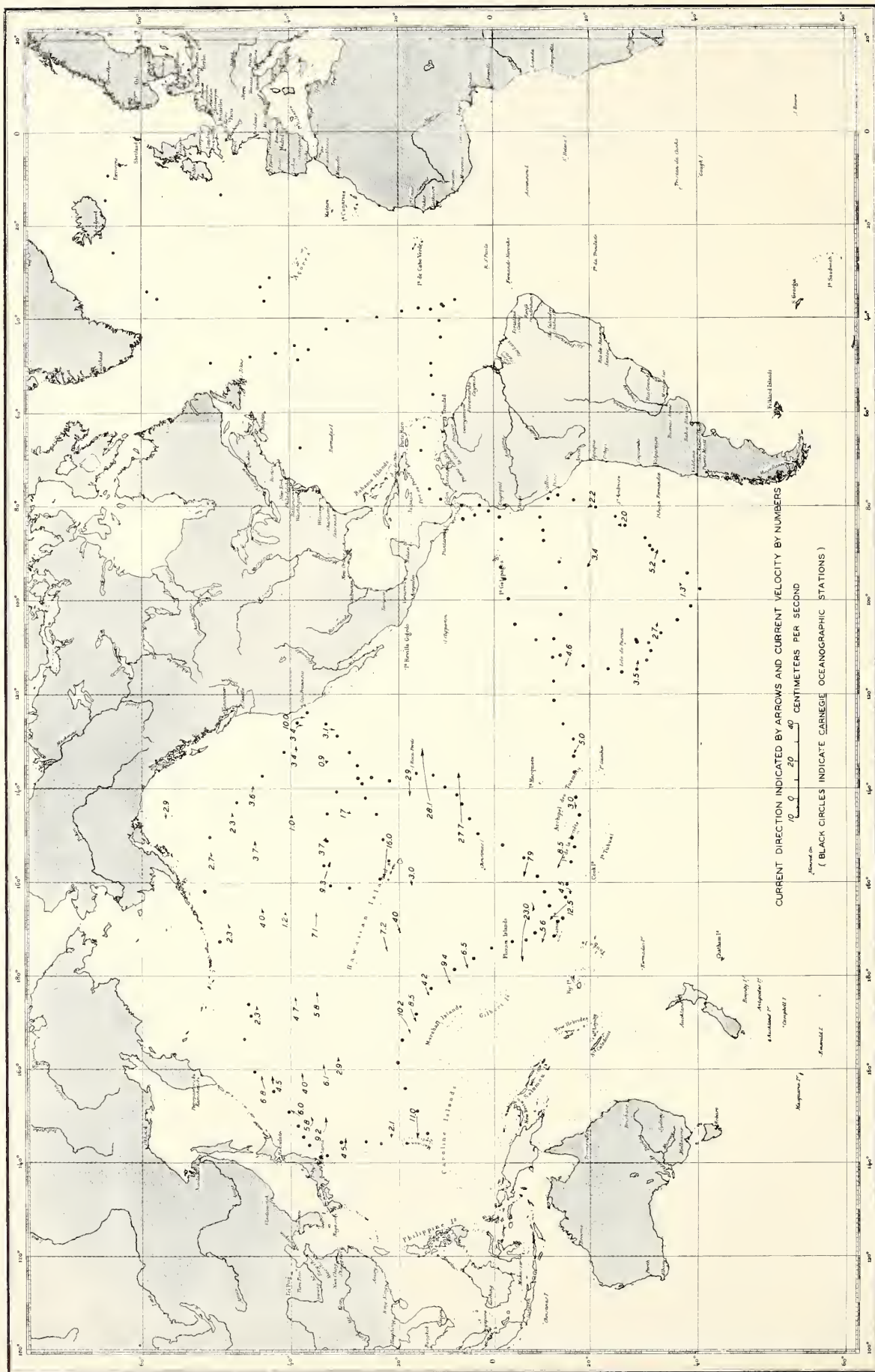
FIG. 36—CURRENT-CHART, PACIFIC OCEAN, AT 200 METERS RELATIVE TO ASSUMED ZERO CURRENT AT 2000 METERS, FROM CARNEGIE RESULTS, 1928-1929

CURRENT DIRECTION INDICATED BY ARROWS AND CURRENT VELOCITY BY NUMBERS
10 0 20 40 CENTIMETERS PER SECOND
(BLACK CIRCLES INDICATE CARNEGIE OCEANOGRAPHIC STATIONS)
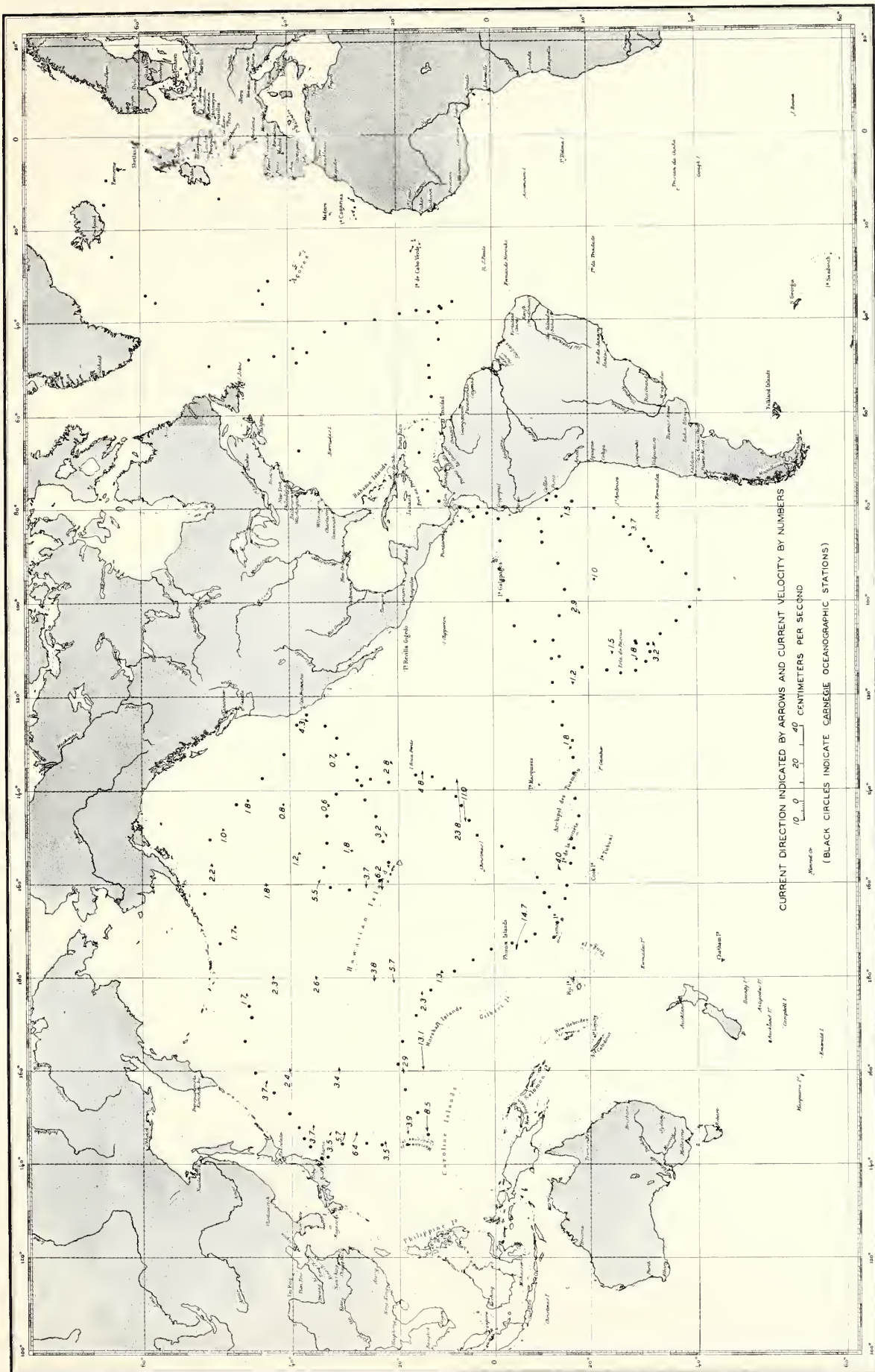
FIG. 37—CURRENT-CHART, PACIFIC OCEAN, AT 400 METERS RELATIVE TO ASSUMED ZERO CURRENT AT 2000 METERS, FROM CARNEGIE RESULTS, 1928-1929

CURRENT DIRECTION INDICATED BY ARROWS AND CURRENT VELOCITY BY NUMBERS

CENTIMETERS PER SECOND

(BLACK CIRCLES INDICATE CARNEGIE OCEANOGRAPHIC STATIONS)

FIG. 38 — CURRENT-CHART, PACIFIC OCEAN, AT 700 METERS RELATIVE TO ASSUMED ZERO CURRENT AT 2000 METERS, FROM CARNEGIE RESULTS, 1928-1929

148
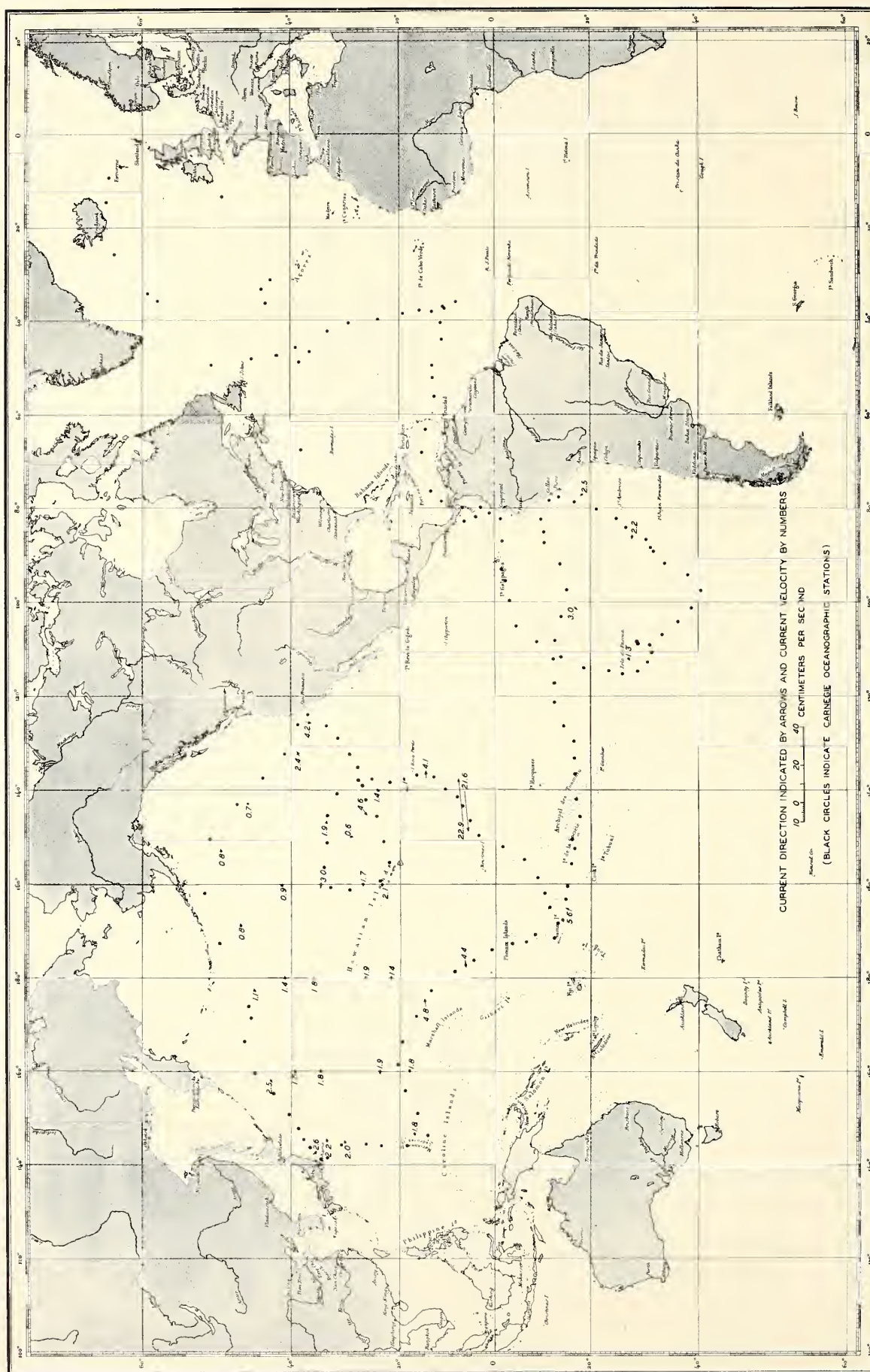
The fact that the scientific program of the <u>Carnegie</u> did not permit of running parallel lines of soundings close together resulted in long single lines of soundings with few intersections. Consequently the data collected cannot be used alone for the construction of a bathymetric chart, but can be used to modify existing charts based on other data and in the construction of profiles along the course of the vessel. Such profiles reveal some of the major features of bottom relief and the general depth level of the oceanic sections traversed.

Attention may well be called to some of the features brought out on the profiles. On profile no. 8 is to be seen what has been named Merriam Ridge in about latitude 25° south and longitude 82° west. Its location with respect to the islands of San Felix and San Ambrosio makes it seem probable that a submarine ridge extends in a general northwest-southeast direction here, and that the two islands are the high points of the ridge.

On profile no. 9 at about latitude 15° south and longitude 98° west, Bauer Deep reaches a sharp depression of about 1500 meters below the nearby bottom. Farther to the west in this profile is the island of Tatakoto at about longitude 138° 20′ west. West of Tatakoto is Amanu Island at about longitude 140° 45′ west and westward of this we see a platform extending from about longitude 141° 40′ west to about 142° 30′ west. This is possibly a part of the platform on which rests the island of Tauere or St. Simeon, just to the north in about latitude 17° 20′ south. West of this platform in about latitude 18° south and longitude 145° west two soundings indicate the crossing of a ridge which is probably the extension to the southeastward of the base of Anaa or Chain Island. In about longitude 148° west is Mehetia Island with depths of more than 3000 meters between it and Tahiti. Farther to the west in the approach to the Samoan Islands, the base of Rose Island is discernible and a depth of more than 3500 meters separates the islands of Tutuila and Upolu.

In profile no. 11 the steep eastern and western approaches to Wake Island are seen at about longitude 166° 40′ east. From Wake Island westward to Guam the <u>Carnegie</u> traversed an ocean whose bottom was previously known to be very irregular and characterized by the submarine mountains such as appear in this part of the profile. Toward the western end of this profile the northern arm of Nero Deep was crossed in about longitude 147° 20′ east with soundings of 7846 and 7448 meters.

At about 24° north latitude in profile no. 12 we see Fleming Deep, in which the deepest of the <u>Carnegie</u> soundings were taken, namely, 8323 and 8347 meters. Soundings taken September 13 to 19, 1899, by the U.S.S. <u>Nero</u> about 30 miles west of the <u>Carnegie</u> positions hint at the existence of the deep but apparently were taken well up on the western slope. It seems probable that the <u>Carnegie</u> soundings also are west of the deepest part. A sounding of 7575 meters shown on Japanese Hydrographic chart no. 6080 at 23° 00′ north latitude, 144° 55′ east longitude, is probably on the southern border of this deep. Heavy weather (including two typhoons) produced so much extraneous noise in the hydrophones that it was impossible to take any soundings between about latitude 31° 40′ north and latitude 33° 20′ north. This was much lamented, as during this period our course lay across

the southern, and what is probably the deepest, part of the extensive Tuscarora Deep. Farther north in this profile, between about latitude 36° north and 37° north, this deep was again crossed.

A newly discovered submarine mountain is shown in profile no. 13 at about latitude 46° 30′ north and longitude 169° 30′ east. It is rather broad, but rises from 1500 to 2000 meters above the surrounding ocean floor.

Between San Francisco and the Hawaiian Islands, and shown in profile no. 14 at about longitude 127° 50′ west, is a submarine mountain which has been named Hayes Peak. This mountain rises precipitously from depths greater than 4000 meters to within 1400 meters of the surface. The charts show a similar mountain about 20 miles WSW1/2W of Hayes Peak. This would suggest an error in position were it not probable that many such submarine mountains exist in this vicinity.

North of Honolulu, and shown in profile no. 16 at about latitude 25° 40′ north, is a rise which has been named Ault Peak. Although it was far from being completely explored, the shallowest sounding over it gave a depth of 2548 meters, indicating an elevation of more than 2000 meters above the neighboring ocean bottom.

In profile no. 21 the northeast and southwest approaches to Penrhyn Island are shown in about longitude 158° west. Similar approaches to Manahiki Island are shown in about longitude 161° west with the trough between the two islands reaching a depth of 5899 meters. Manahiki Island stands as a sharp peak on a broad platform the depth of which is between 2500 and 3000 meters; depths of more than 5000 meters separate it from the Samoan Islands.

Let us now consider how the soundings of the <u>Carnegie</u> require changes in our previous conceptions of the most probable course of the depth contours in the ocean areas traversed. Some base map must be selected for reference and, although it is not up to date in many respects, the Monaco "Carte Générale Bathymétrique des Océans" has been chosen as being most complete and most generally available to hydrographers. Reference is hereafter made to this chart with two exceptions, namely, the area between southern Greenland and Newfoundland, where the reader is referred to part 1 of the Scientific Results of "The <u>Marion</u> expedition to Davis Strait and Baffin Bay," Bulletin No 19, U. S. Treasury Department, Coast Guard, Washington, 1932, and in the region of the seas adjacent to Japan, where reference is made to the Japanese Hydrographic Department chart no. 6080.

On the Norwegian Sea slope and on the Iceland side of the saddle in the Faroe-Iceland Ridge, soundings 64 and 65 indicate that the 500-meter contour line should be moved somewhat to the northeast. On the southeastern coast of Iceland, between longitudes 15° and 17° west, the 1000-meter contour needs to be moved southward to include soundings 75 and 76. The tongue of the 1000-meter contour off Cape Reykjanes, Iceland, requires an S-shape on its western side to pass between sounding 99 and the group 100, 101, and 102. The adjacent 2000-meter contour southwest of here needs to be bent somewhat to the east to pass between soundings 107 and 108. Following this same contour toward the south, another S-pattern is embroidered on it, centered at about 58°

north latitude and 34° west longitude, by soundings 122, 123, 124, and 125. The adjacent 3000-meter line west of this is embayed toward the east to soundings 113 and 114, and passes between soundings 129 and 130. As the Carnegie soundings between southern Greenland and the Grand Banks were considered in the preparation of the bathymetric chart in "The Marion expedition to Davis Strait and Baffin Bay," Scientific Results, part 1, reference is made to that chart for this area.

Again referring to the Monaco chart, two soundings (nos. 21 and 23) of between 3000 and 4000 meters are located within the 4000-meter contour of the East Atlantic Depression. Whether these are isolated peaks or connect with the 3000- to 4000-meter bottom to the west and northwest is open to question. The northern part of the Azores Plateau apparently is more extensive than indicated on the chart, the 3000-meter contour on the eastern side extending to the northeastward to include soundings 19 and 20, and on the western side extending to the westward to include soundings 13 to 17 inclusive. Sounding 18 represents a new peak of the group near Chaucer Bank. Soundings 11 and 12, together with the now altered shape of the 3000-meter contour, make it seem probable that the 3000- to 4000-meter area between latitudes 42° and 44° north and between longitudes 37° and 38° west is connected with the continuous 3000- to 4000-meter belt along the western side of the Middle Atlantic Rise.

East of the southern tip of the Grand Banks the 4000-meter contour needs to be pushed somewhat to the eastward to include soundings 163, 164, and 165, and somewhat south of this, in about latitude 41° 30′ north, needs an indentation to exclude sounding 169. Still farther south between about latitudes 37° 30′ and 38° 30′ north, the 5000-meter line should be extended westward to conform to soundings 175, 7, 176, and 177. Then it is embayed eastward in the vicinity of the 37th parallel in consideration of soundings 178 to 183 inclusive. Soundings 184 to 189 inclusive indicate that this 4000- to 5000-meter arm is connected by means of a low ridge to the general 4000- to 5000-meter belt along the western side of the Middle Atlantic Rise. This leaves an isolated depression of more than 5000 meters depth running northeastward from the ridge just mentioned. As one approaches the Dolphin Plateau from the northwest, the 4000-meter line should be moved somewhat westward to pass between soundings 190 and 191; the 3000-meter contour either cuts the plateau into two sections or is deeply embayed on each side to conform to soundings 197 and 198.

On the eastern slope of the Middle Atlantic Rise in this vicinity, the 4000-meter line is extended sharply southward by soundings 201 to 204 inclusive. Sounding 206 moves the 5000-meter contour eastward. Sounding 208 may either represent an isolated pool or a narrow valley communicating with Moseley Deep. The embayment demanded just south of here by soundings 211 and 213 lend favor to the valley idea. Farther south in about latitudes 15° to 16° north, soundings 220, 221, and 225 may again require the considerable invasion of the Moseley Deep by the 5000-meter contour or they may be isolated elevations. Still farther south in about latitudes 10° to 12° north, this same 5000-meter line takes on a very complicated pattern with a general displacement to the southwestward by soundings 231 to 234 inclusive and 243 to 249 inclusive. Because of lack of data it is difficult to state on which side of the Middle

Atlantic Rise sounding 238 is located, but in either case one of the 4000-meter lines must be altered to accomodate it.

Between about latitudes 11° and 12° north the 4000-meter line on the eastern side of the Middle Atlantic Rise takes on an S-pattern to conform to soundings 253 to 257 inclusive. Crossing the rise at this latitude a 3000-meter contour is required to encircle soundings 261 and 262. The 4000-meter line is extended in a spur to the westward; the isolated area deeper than 5000 meters just to the south of this spur is greatly diminished.

Near here, the southeastern corner of the 5000-meter contour of the West Atlantic Depression is embayed to the eastward so as to pass between soundings 270 and 271, the northern boundary of the embayment following more or less the line of soundings 271 to 282 inclusive. Just east of Barbados the 3000-meter contour line should be moved northward to include soundings 300 to 302 inclusive.

In the Caribbean Sea south of Porto Rico, sounding 315 apparently indicates an isolated peak which must be encircled by a 4000-meter contour. Farther to the west between Haiti and western Venezuela and about midway between them, soundings 318 and 319 indicate the presence of a rise which must be encircled by a 4000-meter contour.

In the southeastern Pacific one of the most important revelations of the Carnegie soundings is that the threshold level of the Easter Island Rise is of a depth less than 3000 meters from about latitudes 9° to 39° south. The 3000-meter contour on the western side of the rise extends in a general northerly direction from about latitude 39° south and longitude 113° west to about latitude 15° south and longitude 115° west, and thence northeastward to about latitude 9° south and longitude 108° west. From this point it curves southward, along the eastern side of the rise, concave toward the east, passing close to the northern side of Easter Island, then extending to the east to include the rocks of Sala y Gomez, then following an irregular course to about latitude 36° south and longitude 104° 30′ west, and then southwestward to close the area. These surmises are based on soundings 373 to 421 inclusive and 543 to 547 inclusive combined with the chart values.

Soundings 424 to 429 inclusive indicate that the embayed 4000-meter line to the south of the Easter Island Rise at about longitude 100° west does not come as far north as has been supposed. Merriam Ridge, disclosed by soundings 458 to 461 inclusive, seems probably to be an extension to the northwest of the base on which rest the islands of San Felix and San Ambrosio. Just north of Merriam Ridge, soundings 463 and 464 require that the 4000-meter contour be moved somewhat to the south; soundings 468 to 471 seem to show that the isolated area of between 3000 and 4000 meters depth is larger than that shown on the chart as a narrow strip between about latitude 17° south and longtiude 75° 30′ west and about latitude 15° south and longitude 77° west.

Soundings 481 and 482 show that the 5000-meter contour of the Milne-Edwards Trench extends farther to the northwest. The 4000-meter line on the eastern side of the Easter Island Rise apparently follows the course of the Carnegie from about longitude 92° west to about longitude 105° west, weaving in and out among soundings 505 to 534 inclusive, with Bauer Deep at sounding 519 as a narrow deep bay.

The caldron in the Easter Island Rise, shown on the

chart between about latitudes 3° and 9° south and about longitudes 100° and 104° west, is modified by soundings 366 to 369 inclusive.

Malpelo Island is shown on the chart as resting on a platform of less than 3000 meter depth, which is connected to the South American continent. Soundings 340, and 343 to 346 inclusive, however, indicate that this platform is separated from the continent by a channel greater than 3000 meters in depth and having a small but deep depression in its middle (sounding 344).

On the western side of the Easter Island Rise soundings 577 to 601 inclusive require that the 4000-meter contour line extend in a long tongue as far west as longitude 131° west in about latitude 17° south.

In the Tuamotu Archipelago soundings 620 to 662 indicate that the 4000-meter line surrounding the northern group includes the islands of Angatau, Fakaina, Rekareka, Taueri, Tatakoto, Pukaruha, and Reao, were it not for the single old sounding of 4000 meters at latitude 18° 08′ south, longitude 141° 49′ west. Soundings 668 and 669 show that the base of Anaa Island extends to the southeastward. In the Society Islands soundings 687 and 688 of more than 3000 meters separate Morea from Husheine; soundings 699 and 700 may mean that a channel deeper than 4000 meters separates Bellingshausen, Scilly, and Mopelia from the rest of the group. West of of Tahiti and south of Raiatea the 4000-meter line needs to be moved south to conform to soundings 694 and 695.

West of the Society Islands in about latitude 16° south the 5000-meter contour is more deeply embayed to the east, as is shown by soundings 712 to 723 inclusive. Following westward along the north side of this bay, this contour continues until about the position of sounding 731 and thence northward nearly to Nassau Island to pass between soundings 1482 and 1483. Northeastward of Danger, Nassau, and Suwarrow islands lies the large submarine platform on which stand the islands of Manahiki and Ryerson. A 4000-meter contour line apparently surrounds this entire area, and a sizable area within this is enclosed in a 3000-meter line (soundings 1458 to 1480 inclusive). Soundings 1452 to 1455 inclusive show a trench of more than 5000 meters between Manahiki and Penrhyn islands.

East of Starbuck Island soundings 1423 to 1426 show the 5000-meter line to be embayed somewhat to the north; depths between Malden Island and Filippo Bank are greater than 4000 meters. At sounding 1415 the bottom is elevated about 800 meters above the neighboring floor.

Between about longitudes 149° and 160° west, the chart shows a 5000-meter contour running in an east-west direction just north of the equator. The chart also shows a 5000-meter line surrounding Christmas, Fanning, Washington, and Palmyra islands. The paucity of soundings southeast of Fanning Island leaves much to conjecture, yet in view of soundings 1389 to 1410 inclusive it seems likely that this area is all of depth less than 5000 meters and that the 5000-meter line runs from a point just west of Jarvis Island northward to meet the chart line at about latitude 2° north, longitude 160° west, that it then follows the course on the chart around the islands mentioned as far as about latitude 7° north, longitude 156° 30′ west, whence it follows the 7th parallel eastward to again join the chart line northward near longitude 149° west. This must remain a conjecture until more data are at hand. Soundings 1403 to 1408 inclusive indicate that a small closed 4000-meter contour is required in this vicinity.

A 5000-meter contour line apparently follows the course of the *Carnegie* from soundings 1332 to 1396, threading in and out among the soundings. This would indicate two things, namely, that an extensive arm thrusts southwestward from what is shown as a caldron centered about 11° north latitude and 130° west longitude, and that the supposed caldron is in communication with and is not shut off from the 5000- to 6000-meter depths of the North Pacific Basin.

Between about longitudes 138° and 144° west an east-west 5000-meter contour is shown between latitudes 24° and 25° north. This needs to be moved farther south to conform to soundings 1314 to 1319 inclusive and 1190 to 1193 inclusive. This same 5000-meter contour farther north, in about latitude 30° 30′ north and longitude 140° west, must be extended northward in view of soundings 1289 to 1292 inclusive.

A sounding (no. 1282) of less than 5000 meters appears at longitude 145° west and a sounding of more than 6000 meters (no. 1250) appears northwest of Murray Deep. The 5000-meter line north of the Hawaiian Islands probably extends northwestward as far as about latitude 28° 30′ north and about longitude 161° west (soundings 1229 to 1238 inclusive). From this base Ault Peak (sounding 1231) rises to a depth of 2548 meters.

The Hawaiian, Gilbert, and Marshall groups are all shown as having a common base of less than 5000 meters depth. The southern part of this 5000-meter contour line is shown on the chart as being just south of the equator and just north of the Phoenix group. Soundings 798 to 824 inclusive seem to indicate that the 5000-meter line is deeply embayed northwestward with a deeper area between the Gilbert and Marshall groups to the southwest and the Hawaiian group to the northeast. The southern part of the 5000-meter line around the Hawaiian group is apparently moved northward to about latitude 3° north to pass between soundings 807 and 808, thence northwestward and returning north between soundings 815 and 816. The line probably continues to the north to connect with what is shown on the chart as a closed depression of more than 5000 meters in the neighborhood of latitude 20° north, longitude 175° west. From the western end of this supposed depression, the 5000-meter line probably continues southwestward, joining the chart line at about latitude 19° north, longitude 178° east. Soundings 839 and 841 seem to show that a low ridge connects this western end of the Hawaiian Rise with the Marshall base near Taongui Island--the northermost of the Marshall group. A small area enclosed by a 6000-meter contour is required by soundings 823 and 824; a 4000-meter line must surround sounding 814. Soundings 830 to 833 indicate another small uncharted rise.

We find from soundings 849 to 859 inclusive that the 5000-meter line surrounding Wake Island extends much farther to the southeast of the island than to the northwest.

Referring now to Japanese Hydrographic Department Chart No. 6080, *Carnegie* soundings 865 to 873 inclusive introduce new contour patterns around the submarine mountains at about latitudes 20° to 22° north and longitudes 162° to 162° east. Additional newly found peaks in this submarine range between this locality and Nero Deep are shown by soundings 883, 896, and 900. On the western border of Nero Deep east of Rota Island, soundings 906 and 907 require the 5000- and 6000-meter lines to be moved more to the eastward.

Soundings 934 and 935 require the introduction in Fleming Deep of an 8000-meter contour, and the extension of the 6000- and 7000-meter lines in this vicinity. South of Fleming Deep sounding 930 shows an isolated peak, and to the north of Fleming Deep another isolated peak is evidenced by sounding 944.

Near the southern end of Tuscarora Deep the eastern 6000-meter line must be moved somewhat more to the east to conform to soundings 948 and 949, whereas farther north sounding 959, on the western slope of the deep, requires the 7000-meter line to be moved to the eastward. East of Tokio soundings 965 and 966 show that the 2000-meter contour and probably the 3000-meter line need to be moved eastward.

Somewhat farther north and on the eastern slope of Tuscarora Deep, soundings 972 to 977 inclusive introduce an S-shaped irregularity into both the 6000- and 7000-meter lines and diminish the area enclosed in the 8000-meter contour.

Soundings 1021 to 1048 inclusive, of which nos. 1022, 1026, 1027, 1032, 1033, 1043, and 1047 are greater than 6000 meters, suggest that a 6000-meter contour runs along the 47th parallel from about longitudes 165° to 175° east, and that this represents the southern boundary of a connection between the Kamchatka Trench and the Aleutian Deep. Soundings taken by the U. S. S. Ramapo have been published by the U. S. Hydrographic Office in a "List of oceanic depths 1931, North Pacific Ocean," H. O. no. 210a, Washington, 1932. Soundings listed in this publication as "route no. 8," on pages 4 to 12 inclusive, parallel the route of the Carnegie somewhat to the southward between Japan and San Francisco. As published, they are based on a constant sounding velocity of 1463 meters per second. Those soundings between latitude 34° 01' north, longitude 140° 41' east, and San Francisco have been corrected for sounding velocity according to the Carnegie data. Comparing these soundings with the Carnegie soundings, there seems to be a low rise on the seaward side of Tuscarora Deep, Kamchatka Trench, and Aleutian Deep, separating these from the deep basin of the North Pacific. A submarine mountain on this rise is disclosed by soundings 1029, 1030, and 1031, with another such mountain indicated by sounding 1038.

Referring once more to the Monaco chart, it would seem from soundings 1050 to 1062 inclusive, of which nos. 1050, 1061, and 1062 are less than 5000 meters, that the 5000-meter contour borders the southern part of the Aleutian Deep as far westward as about longitude 177° west before it turns southeastward.

One other notable departure from conditions indicated on the charts has yet to be considered. This is a wire sounding of 1344 ± 40 meters at oceanographic station 40 in latitude 1° 32' south and longitude 82° 16' west. This was named Carnegie Ridge, but in the absence of other soundings we can only remark that it occurs in an area where the chart shows a depth of between 3000 and 4000 meters.

The names "Carnegie Ridge," "Merriam Ridge," "Bauer Deep," "Fleming Deep," and "Hayes Peak," assigned by Captain J. P. Ault to these various features at the time of their discovery, have been retained in this discussion along with the name "Ault Peak," which was christened after Captain Ault's death.

Some of the profiles of approach to land in the Pacific are shown in the accompanying diagram (fig. 1). These are all islands and are, therefore, shown along with the maximum slope which is theoretically stable according to Littlehales (Bull. Nat. Res. Council, no. 17, pp. 90-93, 1922). Inasmuch as some of these islands have an appreciable mass above the water level, a strict comparison is not justifiable. In order to better compare the actual bottom slopes, all the curves have been started from the shore line and the distance of the center of the peak from the shore line has been given in tabular form to enable the reader to differentiate between the large and small islands. Of the nine islands, the approaches for which are shown, four are grouped as large and five as small. An interesting feature which offers food for thought is that four of the five small islands shown have a secondary ridge or elevated prominence on their northeastern sides, whereas the fifth (Wake Island) was not approached from this direction. In the case of Penrhyn Island, this ridge apparently comes very close to the surface and is known as Flying Venus Reef. The data are, of course, too meager for conclusions, and the absence of similar ridges on the other sides of these islands, as indicated by the Carnegie soundings, may be owing to too great an interval between soundings, rather than to the actual nonexistence of such irregularities. In the case of Amanu Island, the apparent irregularity may not be real and may only be the result of the devious path of approach.

These findings, as well as the entire sounding program of the Carnegie, stress the need of more thorough exploration of the ocean depths and impress one with the inadequacy of our present knowledge of the bottom features.
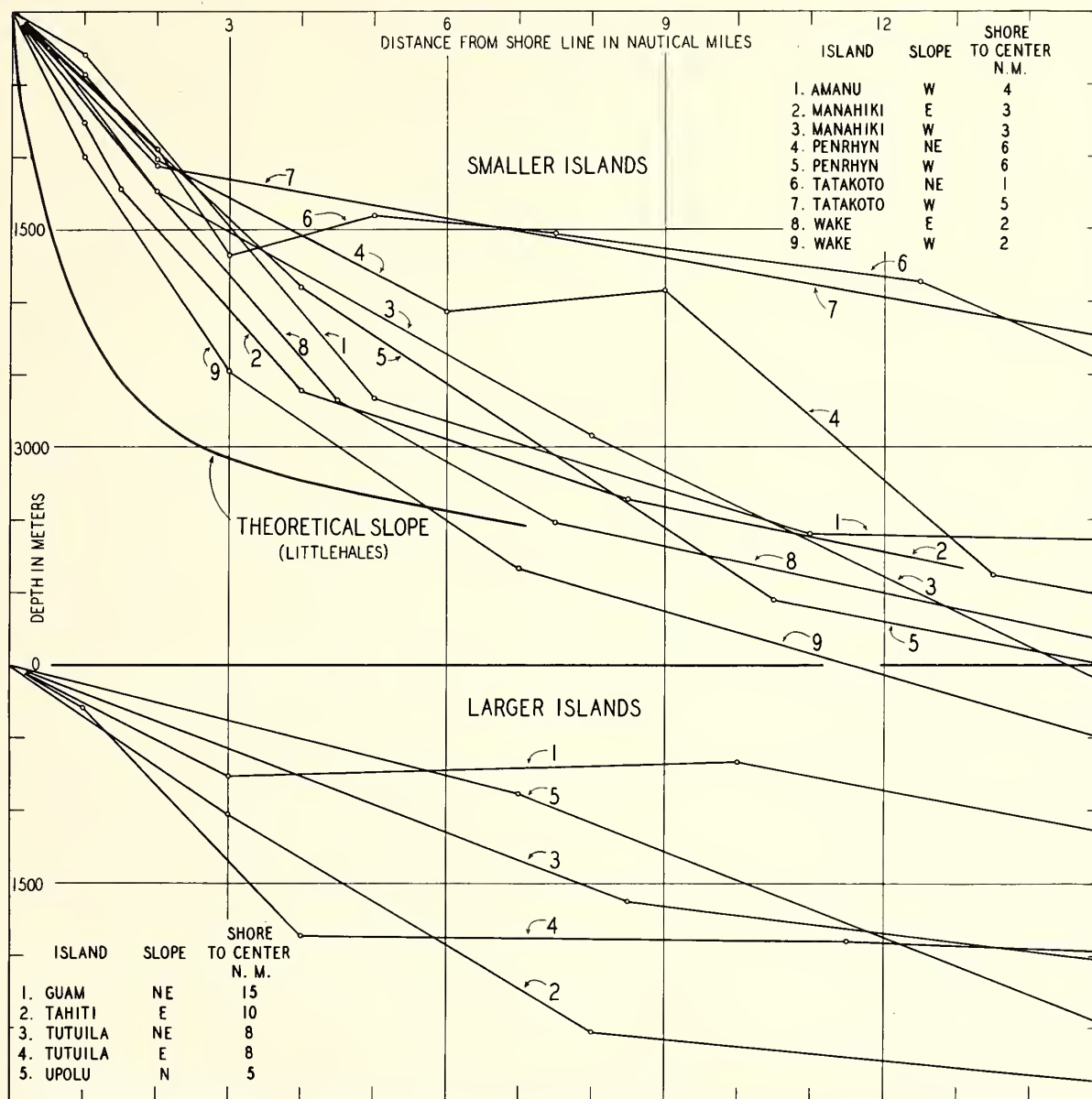
FIG. I—SLOPES OF ISLANDS AS DEVELOPED FROM SONIC-DEPTH RESULTS ON CRUISE VII OF THE <u>CARNEGIE</u>, PACIFIC OCEAN, OCTOBER, 1928, TO NOVEMBER, 1929

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